

# Applications of Digital Holography to Microstructures

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## ABSTRACT

Non contact and full field optical measuring techniques have become an important tool for investigating microstructures. Generally, either the phase or the amplitude of light reflected from a surface is analyzed. As a consequence 3D information can only be received by using scanning techniques.

Digital holography offers the simultaneous measurement of amplitude and phase and therefore allows complete measurement without scanning procedures. This feature allows new applications, esp. if objects are moving or even vibrating. In this paper we will show the principle and some examples of the application of digital holography.

## INTRODUCTION

In digital holography a hologram is recorded by an electronic device and reconstructed digitally by simulating the reference beam. The idea was already published more than 30 years ago by, for example, Goodman and Laurence /1/. However, it took several decades of improvement of computer and imaging technology as well as an understanding of the theory to develop a digital holography microscope which can be used as an optical measuring instrument to analyze mechanical problems. Major work has been carried out by two groups headed by W. Jüptner at Bremer Institut für angewandte Strahltechnik (BIAS) /2/ and C. Depeursinge at Ecole Polytechnique Fédérale Lausanne (EPFL) /3/. However, the major breakthrough was the development of a method for direct reconstruction of the phase distribution by Cuche, et.al. /4/.

Meanwhile, digital holography has reached a technical level which allows it to be used as a measuring tool and as an instrument for analyzing microscopic structures in real time with high resolution. The technique has mainly been developed for transmission microscopy. However, it can also be applied to solid mechanics with great advantages.

## PRINCIPLE OF OPERATION

The scheme of the optical set-up is shown in fig. 1. The beam of a diode laser ( $\lambda = 682.5 \text{ nm}$ ) is split into a reference wave (R) and the object wave (O). The light reflected by the surface of the sample is combined with the reference beam. Both beams generate the hologram on the CCD of the camera. Contrary to classical holography, the object wave is now reconstructed by digital means. Using the formulas of Fresnel diffraction, the original wave reflected from the sample is reconstructed digitally in three dimensions.

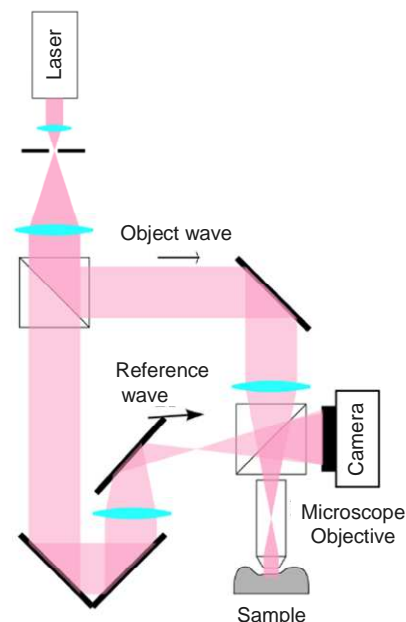


Fig.1: Set-up of a digital holography microscope /5/

In fig. 2 the phase information of the object wave is shown. The originally plane wave front illuminating the sample is reflected from the surface. Following the Huygen's principle of elementary waves, the reflected wave front is deformed according to the surface geometry of the object. The superposition of the (also plane) reference wave and the reflected object wave forms an interference pattern which is recorded by the CCD camera, fig. 3. A detailed view of such a hologram, fig. 4 shows the typical interference structure of such superposition.

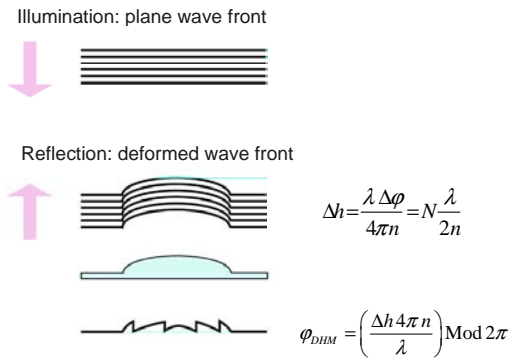


Fig. 2: Formation of phase in a digital holography microscope

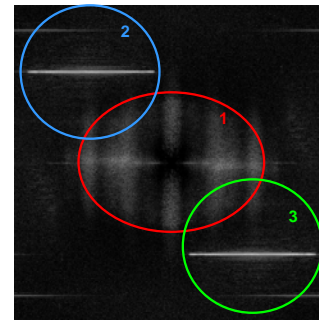


Fig. 5: Fourier transformation of hologram

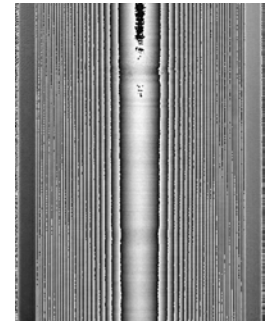


Fig. 6: Phase of a cylinder lens

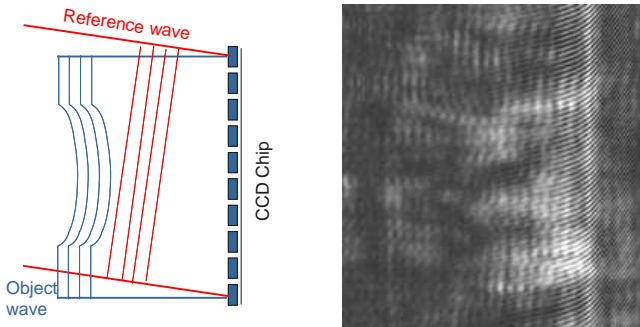


Fig. 3: Superposition of reference and object wave

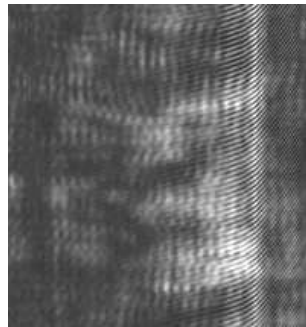


Fig. 4: Enlarged section of the hologram

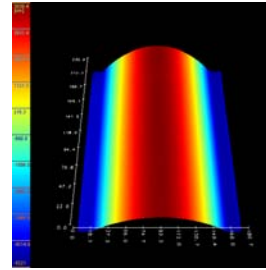


Fig. 7: Phase image (shape) of a cylinder lens

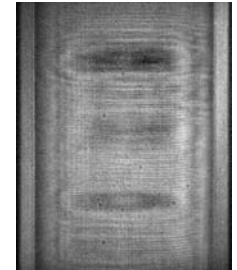


Fig. 8: Intensity image of the cylinder lens

The information stored in the hologram is the superposition of the complex reference wave  $E_R$  and the object  $E_O$  wave. The camera records the intensity of both waves, which is calculated by the following formula

$$|E_O + E_R|^2 = |E_O|^2 + |E_R|^2 + E_O E_R^* + E_O^* E_R$$

As can be seen, the hologram contains the square functions of the object wave  $|E_O|^2$  and the reference wave  $|E_R|^2$  and the two conjugate terms  $E_O E_R^*$  and  $E_O^* E_R$  which contain the phase information of the object wave in the hologram. The Fourier spectrum of the hologram shows these elements. As an example, the Fourier spectrum of a hologram of a cylinder lens is shown in fig. 5. Area 1 describes the object and reference waves, while areas 2 and 3 represent the two terms of interest containing the phase information. The selection of area 2 and a back transformation generate the required phase information, fig. 6.

However, the phase information is modulated by  $2\pi$  due to the ambiguity of interference effects. Therefore, in a following step, the phase distribution has to be unwrapped to generate the shape of the object, fig. 7. Similarly, the intensity image of the object can be generated by the digital holography microscope, fig. 8. It can also be observed that the image quality of the intensity image is influenced by speckle effects.

In comparison with classical microscopic 3D-measuring techniques (confocal microscope, white light interferometer, etc.), digital holography offers the advantage of recording the 3D shape of the surface with one single hologram. Consequently, even moving objects can be investigated. Using stroboscopic illumination or a triggered camera, even vibrations can be analyzed with this technique. The speed of data acquisition depends on the transfer rate of the camera and is typically 15 Hz. The calculation of the wave front is carried out at the same speed. So observation of the object wave front can be performed in real time.

Of course, such a technique also has its limitations. As can be seen from the phase distribution in fig. 6, spatial resolution of the system has to be large enough to resolve phase changes between neighboring pixels. If the fringe density is too high, the phase distribution cannot be resolved properly and the unwrapping algorithm will cause errors. If the phase differences between object and reference wave vary even within one single camera pixel, no valid data will be generated at all. New developments try to overcome these limitations by using multiple wavelengths and generating a kind of synthetic wavelength,  $\lambda/6$ .

## APPLICATIONS OF DIGITAL HOLOGRAPHY

### MEASUREMENT OF OPTICAL COMPONENTS

A digital holography microscope system can be used for the inspection of micro-optical elements, such as the cylinder lens shown in the examples above. Other application examples are micro lenses.

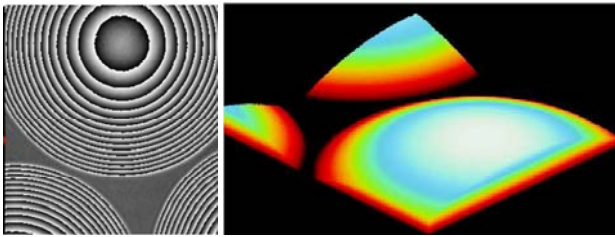


Fig. 9: Phase image and shape of a micro lens array

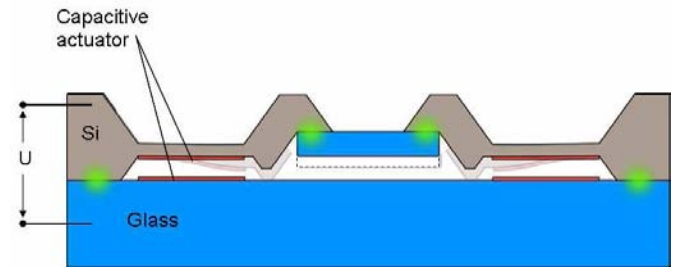


Fig. 11: Design of tunable etalon

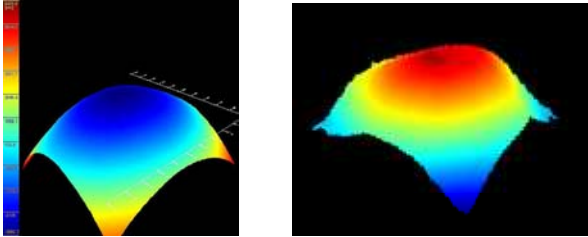


Fig. 10: Outer and inner contour of a plastic micro lens

While fig. 9 shows a section of a micro lens array as a phase map and as a 3D plot, in fig. 10 the result of the contour measurement of a plastic micro lens is demonstrated. Measurement was carried out with a 10x objective, giving a horizontal length of ca.  $700 \mu\text{m}$ . The outer surface of the lens shows comparably good quality (left). The principle of digital holography offers a measurement volume, which is laterally limited by the field of view of the microscope objective. In vertical direction, it is limited by the coherence length of the laser used. In our case, the coherence length of the laser is selected to just  $0.5 \text{ mm}$ . This helps to avoid any interference within the microscope objective. Therefore, moving the microscope down in vertical direction allows a vertical scan through the lens and measurement of the inner surface of the lens from the same measurement direction. In the right of fig. 10 the result is shown. It can be observed that the surface quality is fairly reduced. However, we have to take into account that digital holography measures the distances of the optical path. Therefore, this result does not directly represent the inner surface of the lens. It also contains the contour of the surface and at the same time any variations of the optical parameters within the lens material.

## 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. 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 [7], fig. 11. A silicon structure with capacitive actuator carries a glass window. When a voltage is applied, the glass window is moved towards the glass carrier, thus reducing the gap between window and glass carrier. In fig. 12, top left, the etalon and its dimensions can be seen. The symmetric design guarantees parallel movement of the glass window.

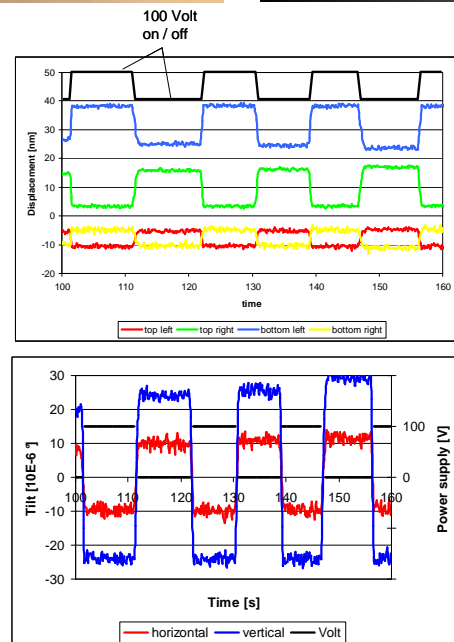


Fig. 12: Measurement of the movement of the tunable etalon

The movement of the glass window was analyzed with digital holography. Four measuring points were defined in the corners of the glass window and the center was defined as reference, fig. 12. Then the movement of the window was measured while voltage was applied. The reference point always stabilized the center of the image to the same phase (amplitude). When a voltage of 100 volts is applied, the glass window moves approx.  $1 \mu\text{m}$ . At the same time, the relative movements of the corner points are in the range of  $10 \text{ nm}$ . From the horizontal and vertical differences in dislocation the tilt angle can be calculated. In both directions it is less than  $0.1^\circ$ .

## THERMAL LENS EFFECT OF 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, fig. 13. This effect is called thermal lens effect and can result in worse performance of the laser. The heating of the NdYAG crystal may also cause the refractive index of the crystal material to vary; however, the mechanical effect of deformation has a much higher influence on the performance of the laser. Therefore, the thermal lens effect was investigated by means of digital holography, /8/.

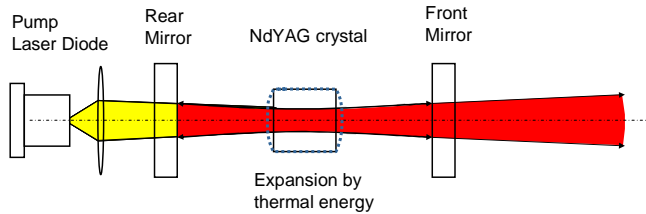


Fig. 13: Thermal lens effect in a NdYAG laser

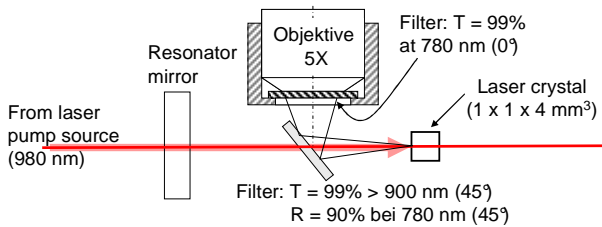


Fig. 14: Experimental set-up

A selective filter was implemented into the laser resonator just in front of the laser crystal, fig. 14. The filter allowed the pump laser light at 980 nm and the laser light itself at 1064 nm to pass with a transmissivity higher than 99%. The measuring wavelength of the digital holography microscope (682.5 nm) was reflected with 90% reflectivity into the 5X objective of the microscope. During measurement, the laser was pumped with the diode laser at different pump currents and emitted light. In order to prevent any laser light from penetrating into the microscope objective, an additional filter was mounted directly in front of the objective. With this set-up, the deformation of the surface of the laser crystal could be measured during laser operation.

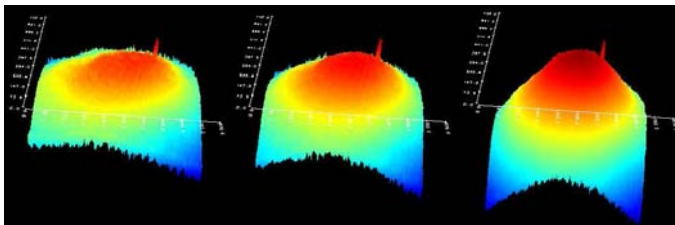


Fig. 15: Deformation of the crystal surface

Fig. 15 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 brought into the crystal, fig. 16.

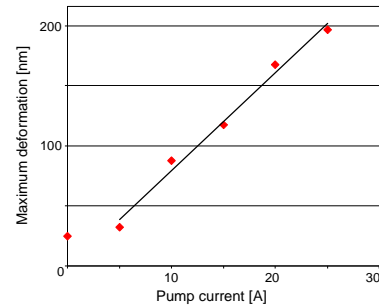


Fig. 16: Relation between deformation and pump current

## MOVEMENT OF THE CANTILEVER OF AN ATOMIC FORCE MICROSCOPE

One advantage of digital holography is the fact that just one single image is required to obtain complete 3D information of the measured surface. Therefore, measurements can be carried out very quickly if enough laser illumination energy is available and the camera shutter can be reduced to a few microseconds. In case of harmonic vibrations of the measuring object a stroboscopic technique can be used.

There are two options for stroboscopic measurement, see fig. 17:

### 1. Stroboscopic mode

The camera shutter opening is synchronized with the vibration excitation signal. If  $n$  images are to be recorded during a complete vibration period  $T$ , the first image is recorded at any position, e.g.  $t_0$  and the following images are recorded after certain time intervals  $T/n$ . The first image is recorded at  $T/n$ , the second at  $2T/n$  and so on, until a complete vibration cycle has been finished. As all images can be analyzed within one camera cycle, at the end of the sequence the result can be displayed as a video animation.

### 2. Pulsed mode

If vibration frequency or amplitude is too high and camera shutter time has to be reduced to a value which does not allow enough light to be collected within one image, a pulsed mode is used. The laser is modulated with short laser pulses and several laser pulses emitted at the same phase of the vibration signal are collected by the camera and added. However, this procedure takes significantly more time than the stroboscopic mode but can deliver results even at high frequencies up to 100 kHz.

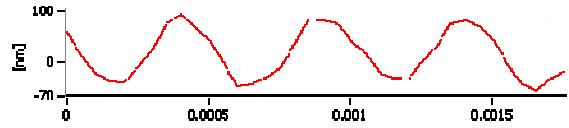
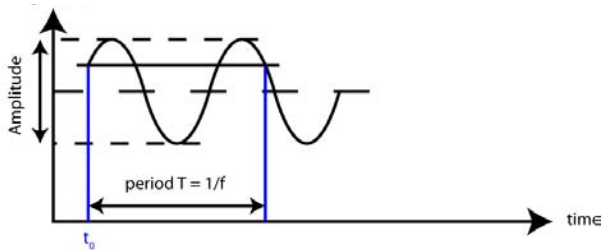


Fig. 19: Vibration amplitude of cantilever tip

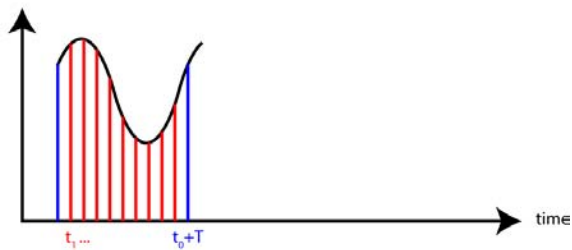
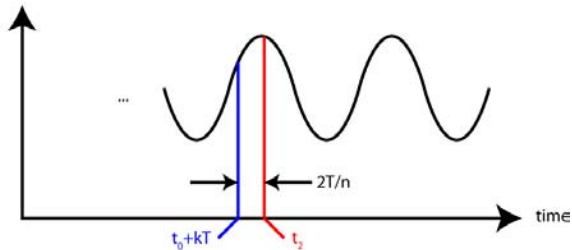
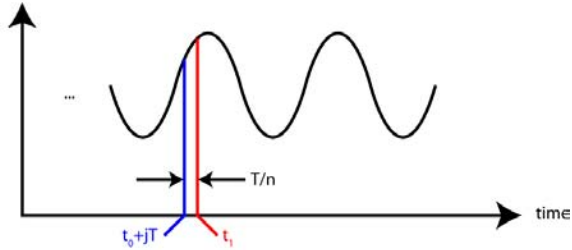


Fig. 17: Principle of vibration measurement

The following example shows the vibration of the cantilever of an atomic force microscope (AFM). The best way to see the vibration is to observe the change of phase at different recording times. Fig. 18 shows the phase map at 2 different time settings during one complete vibration cycle. The right image shows the 3D display of the cantilever.

As each hologram is stored separately, the time-resolved displacement can be received at any point in the image. Fig. 19 shows the vibration of the tip of the triangular cantilever.

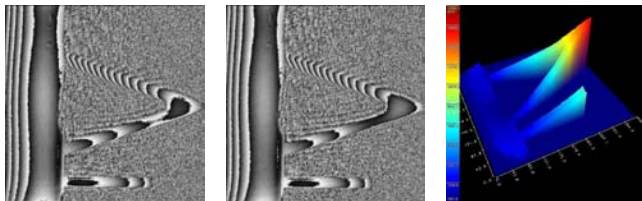


Fig. 18: Phase map of cantilever at different time positions and 3D display

## CONCLUSION

Digital holography offers interesting new possibilities for the investigation of small components and surfaces. The ability to simultaneously determine amplitude and phase of an object with just one single image may open up new applications, e.g. under rough environmental conditions, for quality inspection in the production line, etc. This relatively new technology opens new possibilities for investigating microstructures which have yet to be defined in future.

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