INFORMATION MODELLING OF TWO-DIMENSIONAL OPTICAL PARAMETERS MEASUREMENT

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Abstract: A method for measurement and visualization of the complex transmission coefficient of 2-D micro-objects is proposed. The method is based on calculation of the transmission coefficient from the diffraction pattern and the illumination aperture function for monochromatic light. A phase-stepping method was used for diffracted light phase determination.

Keywords: microscopy, phase-stepping method, interferometry, inverse problem in optics

Introduction

The optical characteristics of different objects are an indicator of their state (cells), production quality (optical elements), homogeneity (solutions and gels), etc. For measurement of these characteristics various laboratory and industrial measuring systems are exploited. The most common building elements are light source, imaging optical system (mirrors, objectives, beam splitters, etc.) and photosensitive (recording) device. Sometimes the utilization of an objective for the measuring system is undesirable, more expensive or even impossible. For that reason, new methods for micro-objects optical parameters calculation on the basis of information, derived in the Fraunchofer zone, are under development.

Method of Measurement

The method of measurement is based on the inverse problem in optics [1] - the object transmission function is derived from the known intensity distribution function of the illuminating beam aperture and the measured intensity distribution on a screen behind the object. It is known that the phase-stepping method [2] allows measurement of the light complex amplitude. The simultaneous use of the phase-stepping method and diffracted light intensity measurement makes possible the calculation of the transmission coefficient in a complex form. To eliminate the unknown parameters of the illumination system, information from additional reference measurements is used.

Set-up

An exemplary interferometric set-up is shown in Fig.1. The light beam from the laser source (L) is split by the beam splitter (S1) into an object beam (OB) and a reference beam (RB). The object beam passes through the investigated object (O) and the transmitted light is detected by the CCD camera (CCD). The reference beam after being reflected by a phase-stepping mirror (pH), passes through a lens (LN) and illuminates the CCD camera.

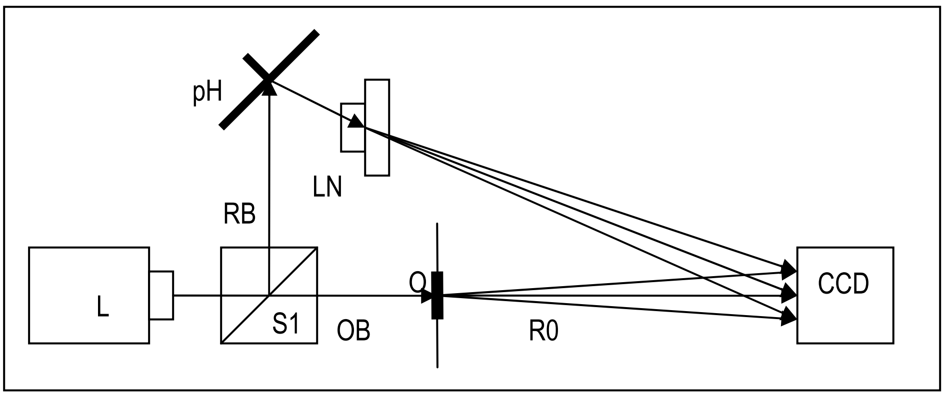

Fig. 1.

Approximations and Applicability

In this investigation the 3-D objects are approximated with 2-D objects and we suggest that the objects are thin. With this approximation we can find a single solution. For real 3-D measurements, a tomographic method could be used, based on recording a set of images while the CCD is moving towards the object.

Scattering and reflection, as optical parameters of the object, are not taken into account. These parameters can also be ignored when measuring a large class of objects..

Utilizing light with a wavelength of 0.5-1.0 μm is limited by the CCD sensor characteristics. According to Abbe's theory, using shorter wavelengths results in higher measurement accuracy.

Normally, the size of the CCD sensor is 5-10 mm. This limits the range of the usable spatial frequencies. When the illuminating beam has an aperture of about 5 μm and the amplitude and the phase are constant over the whole cross-section, the spatial frequencies are localized within an angle of about 5 deg, but if the aperture is a periodical structure (grating) with a spacing of 1 μm, this angle increases to 45 deg. In order to make use of all the spatial frequencies, the CCD camera must be placed close to the object, which means that the object may fall outside the far-field (Fraunhofer) zone.

The theoretical investigations of the errors, resulting from the spatial localization of the CCD sensor, ADC precision, pixelization, object thickness and its optical characteristics are an important part of the experimental set-up preparation. The difficulties in ensuring some of the conditions can prove a barrier, given the present state of the hardware.

Mathematical Model

When the distance between the object and the recording plane is much greater than the object size, the recorded intensity distribution can be approximated with a Fourier transformation of the object image [3,4]. In this case the total light intensity resulting from the combination of the object and the reference beams and measured by the CCD camera is given by:

$$A = [F(O.R0) + R1]^2, \tag{1}$$

where A is the intensity of each pixel, O is the object transmission function, $R0$ is the amplitude distribution function over the object beam aperture, $R1$ is the amplitude distribution function over the reference beam aperture and F is the Fourier transformation.

Taking the second power of the expression, we get:

$$A = [F(O.R0)]^2 + R1^2 + 2F(O.R0).R1. \tag{2}$$

From (2) it is seen that the first and the second additives represent the intensity from the object in the absence of reference and from the reference in the absence of object. In order to eliminate these terms, two separate measurements (two frames) must be conducted:

$$O2 = [F(O.R0)]^2 \tag{3}$$

and

$$R2 = R1^2. \tag{4}$$

For each frame A the corresponding corrected B is calculated, where:

$$B = (A - O2 - R2)/2 = F(O.R0).R1 \tag{5}$$

Using phase shifting (4-steps method) of RB the image ($B4$) can be calculated, which is the Fourier transformation of the aperture of the corresponding illuminating system in the frequency domain.

$$O.R0 = F^{-1}(B4) \tag{6}$$

Finally, a reference measurement must be provided to eliminate $R0$. It represents a measurement without an object and its physical essence is measurement of the aperture function of the measurement system. In this way, the influence of many inaccuracies in setting the measurement system parameters, such, as illuminating beam intensity distribution, measurement aperture geometry, reference beam and its parameters are compensated.

$$R0 = F^{-1}(Br4) \tag{7}$$

$$O = F^{-1}(B4)/R0 \tag{8}$$

O is a matrix of complex numbers. The modulus describes the attenuation and the argument – the phase shift for each point of the measured object.

Information Model

A program is written for simulation of the set-up on Fig.1 and processing of the information, derived from the CCD camera. The program is used to evaluate the requirements to the set-up and the constraints to the method applicability. The program is written in C++ for a PC platform. In some cases an FFT algorithm is used, but a direct integration version is also developed, due to the fact that the requirements for applying FFT cannot be always satisfied.

The object is chosen to be an amplitude (and/or phase) plate with a transmission function O = k0 + k1 SIN (k2 X). A photograph of an amplitude plate is shown in Fig. 2. The distribution function of the reference beam is chosen to be R0 = n0 + n1 SIN (n2 Y). The amplitude distribution is shown in Fig. 3.

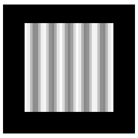

Fig.2 Measured object (simulation formula)
O (x, y) = 1+0.3 SIN (kX))

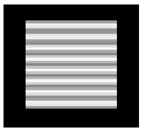

Fig.3 Measuring system aperture
(simulation formula)

This choice is made, in order to observe the interference pattern and the mutual influence of the aperture function and the object beam. The values of the pixels in each calculated image is rounded to 0.5 % of the maximum. The idea of this choice is to simulate the most popular 8-bit ADC used in frame grabbers.
Fig.4 shows amplitude and phase maps of the object function calculated by Fourier transformation.

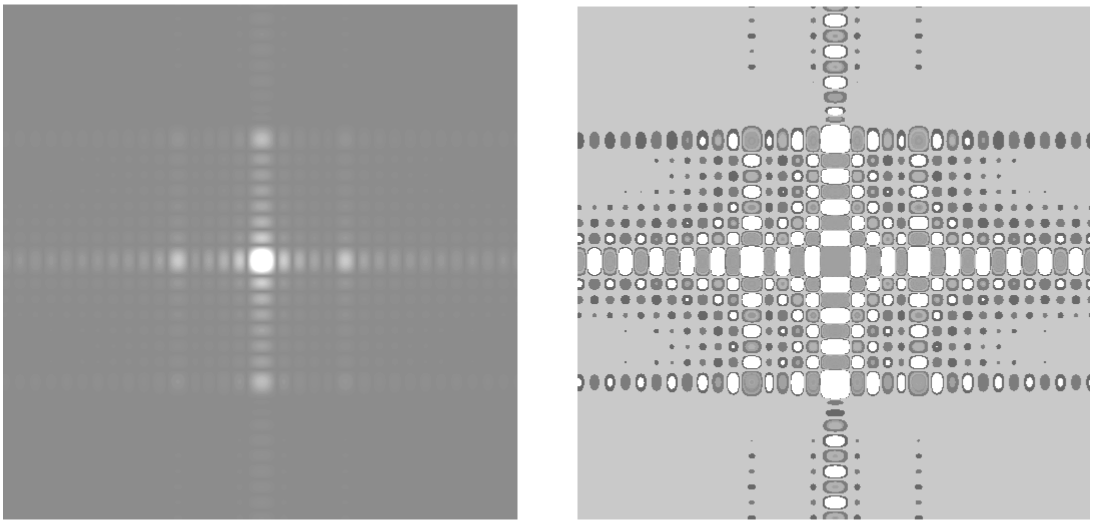

Fig.4 Final information before the reverse Fourier transform: amplitude and phase maps

The images in Gig.5, 6 and 7, obtained after application of the inverse Fourier transform, are close to the input.

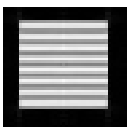

Fig.5 Calculated system transmission function distribution

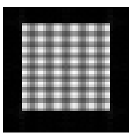

Fig.6 Calculated object + system distribution

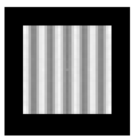

Fig.7 Calculated object

In the inverse calculation, due to rounding of the values of some pixels, the object function takes very high values – more than 50 times higher than the measured value maximum. This requires the use of a "window"-function to mask the undesired and unexpected results. The masking function (Fig. 8) is calculated from the distribution and replaces the calculated values. To eliminate small single spots, a smoothing filter with a suitable aperture (2-10 pixels) is used.

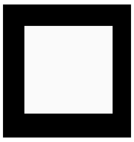

Fig.8 Calculated window of valid information

Fig.9 shows the transmission coefficient distribution in the middle of the image (in the cross-section), which, in that case, is simulated with values even greater than unity.

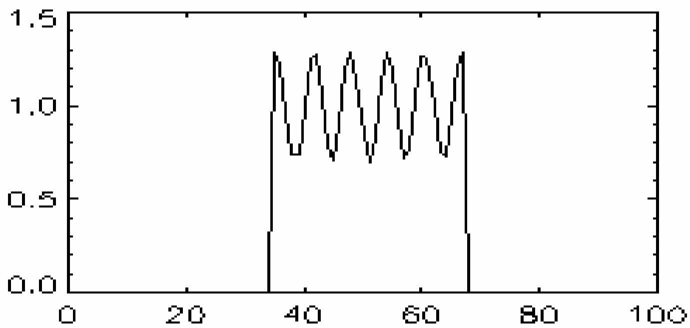

Fig.9 Cross-section of the intensity in the middle of a reconstructed image

Discussion and Conclusion

The proposed approach for measuring the optical characteristics of 2-D objects is very suitable for in-situ observation of living cells. The results of the modeling give us grounds to claim, that it is possible to use 8-bit ADC for visualization of phase objects. If this technique is to be used for measurement, an ADC with higher resolution is needed. The laser power and the CCD sensor sensitivity are essential, because the object can be damaged by the higher energy density. The investigation of living cells in liquid media can be realized by the use of pulsed laser.

Measurement of objects larger than 5-10 μm requires positioning of the CCD camera at a distance of more than 0.1-0.2 m from the object. In this case, this method is unsuitable and even impossible. On the other hand, the observation of small objects leads to an increase in the high-frequency components of the spatial frequencies. A CCD sensor with large sensitive area is required for the registration of these spectral components.

References

1. Baltes H. P., Inverse Source Problems in Optics, Springer-Verlag Berlin-New York, 1978.
2. Tiziani H.J., Optical methods for precision measurements, Optical and Quantum Electronics 21 (1989) 253-282.
3. Cowley J. M., Diffraction Physics, North-Holland Publishing Company, New York, 1975.
4. Rastogi P., Sharma A., Systematic approach to image formation in digital holography. Opt.Eng.42(5) 1208-1214 (May 2003).

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