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2013

Qu, W., Wang, Z., Cheng, C. Y., & Asundi, A. K. (2013). Compound common-path digital holographic microscope. Proc. SPIE 8644, Practical Holography XXVII: Materials and Applications, 864414.

<https://hdl.handle.net/10356/98371>

<https://doi.org/10.1117/12.2003755>

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Compound Common-path Digital Holographic Microscope

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Digital holographic microscopy provides 3D quantitative phase imaging that is suitable for high resolving investigations on reflective surfaces as well as for transmissive materials. An optical configuration for a digital holographic microscope and a method for digital holographic microscopy are presented. A cube beam splitter in the optical path, with a small angle between the optical axis and its central semi-reflecting layer, both split and combine a diverging spherical wavefront emerging from a microscope objective to give off-axis digital holograms. Since the object wave and the reference wave go the same way to the CCD camera, it is called common-path digital holographic microscopy. When a plane numerical reference wavefront is used for the reconstruction of the recorded digital hologram, the phase curvature introduced by the microscope objective together with the illuminating wave to the object wave can be physically compensated. A compound digital holographic microscope (with reflection mode and transmission mode) has been build up based on this unique feature. Results from surfaces structures on silicon wafer and micro-optics on fused silica demonstrate applications of this compound digital holographic microscope for technical inspection in material science.

Keywords: digital holographic microscopy, physical phase compensation, 3D quantitative phase imaging

1 INTRODUCTION

Microstructures become more and more important in our everyday life. Taking use of micro-optics, wafer-level camera¹ enables an even smaller size of digital cameras, mobile phones, portable gaming consoles, laptops or netbooks. Micro-Electro-Mechanical Systems (MEMS) devices have been successfully used in inkjet printers, accelerometers for cell phones, digital micro-mirror device (DMD)² for projectors, and other applications. These microstructures are not simple component but serious stacking of different components. Taking the wafer-level camera as an example, the lens wafers are aligned and bonded into integrated optical elements and mounted onto a packaged image sensor. One may need to do optical testing of the transparent lens in the different processing steps as well as the opaque final products. Powerful inspection equipment is needed to ensure the reliability of these microstructures.

Digital holographic microscopy (DHM) allows the retrieval of quantitative phase information through a single image acquisition. It is an ideal tool for 3D topographic characterization and real-time dynamic inspection for life science living cells, MEMS/MOEMS, micro-optics, microtechnology and nanotechnology. It is also known as quantitative phase microscopy. Many research works have been done on this quantitative phase measurement technique.

Usually there is different optical component in the two paths of the DHM system. The object path is designed for imaging the test sample by using of a microscope objective (MO). The MO will change the divergence of the object wave and results in a wavefront aberration between the object and reference waves. This wavefront aberration must be removed from the detected phase to obtain the phase of the test specimen. There are two ways to remove the wavefront aberration. One is the numerical phase compensation method in the numerical reconstruction process. It is to calculate a phase mask to be multiplied by the recorded hologram or by the reconstructed wave field in the image plane³⁻⁵. The other is the physical phase compensation method in the optical recording process. It is to build the optical interferometer with two equivalent interference wavefront. In the practical instruments both methods are applied. For DHM system in transmission mode⁶, a reference plane can be employed to do subtraction for the phase compensation. But for DHM system in reflection mode, numerical phase compensation must be done to obtain the quantitative phase measurement⁷. As such, this limits the DHM system to be built either as a standalone transmission-configured or reflection-configured system but not both.

In our previous work, we found that phase aberration free DHM can be achieved by a common-path DHM system based on a single cube beam splitter (SCBS) interferometer⁸ using a microscope objective (MO)⁹ or diverging spherical wave¹⁰

to provide magnification to the test specimen. Since the object beam and reference beam share the same optical path, the wavefront curvatures can physically compensate each other during the interference. In this paper, we propose a compound DHM system which can measure the transparent specimen (living cells, micro-optics) as well as the opaque specimen (pattern on wafer, MEMS). It is based on the common-path DHM (CPDHM) system. The unique way of CPDHM to get the digital hologram enables the transmission mode to be built together with the reflection mode. Various measurement results are given to show the performance of the system.

2. Principle of Compound Common-path DHM system

1. SCBS microscopy system working as DHM system

Here, we briefly recall the principle of the SCBS microscope working as a digital holographic microscope as was clearly introduced in reference [9]. Digital off-axis holograms can be recorded by using an SCBS in a non-conventional configuration so as to both split and combine the wavefronts emerging from a microscope objective. As shown in Fig.1, light incident on the SCBS is split into two paths by its front edge. Each path of the light will change its propagation direction inside the SCBS. The refracted light arriving at the central semi-reflecting layer will be both reflected and transmit to the back cube wall. The wave reflected from the left optical path will combine with the transmitted wave from the right optical path at the exit of the SCBS. Since there is a small angle between the direction of light propagation and the central semi-reflecting layer, a wedge-shaped optical path difference will be introduced between the reflected light and the transmitted light. Thus, two phase-shifted interferograms can be obtained at the back edge of the SCBS. Each one can be captured by the CCD camera and numerically reconstructed to give the phase of the test object. As it is a common-path interferometer, the reference arm travels the same distance as the object arm. Their spherical phase curvatures are physically compensated by each other during interference in the digital hologram recording process. In the numerical reconstruction process, the off-axis tilt is physically compensated by moving the selected spectrum to the center of the calculation plane. It is limited by the pixel size and may sometimes leave a sub-pixel off-axis tilt uncompensated. In such a case, a plane reference wave can be calculated based on the fitting procedures of the reconstructed tilt for the DHM system without the test specimen. This calculated plane reference wave must be multiplied by the digital hologram in the numerical reconstruction to include sub-pixel off-axis tilt compensation and give a flat phase surface. Under this condition, the phase introduced by the test object can be easily acquired by only one shot without any numerical phase compensation procedure.

Fig.1. Schematic of the compound common-path digital holographic microscope.

2. Compound common-path DHM system based on SCBS microscopy system

The capability of physical phase compensation in SCBS microscopy system enables DHM system to be build both in

transmission mode and reflection mode. The schematic of the compound common-path DHM system is shown in Fig.1. The transmission path and the reflection path share the same optical components. Thus the two modes can be integrated into one system.

3. Prototype of Compound DHM system

1. Prototype of common-path DHM in transmission mode

A picture of the common-path DHM in transmission mode is shown in Fig.2. Light emitting from a HeNe laser is coupled to a fiber output to serve as the source. The test specimen is held by a xyz motorized stage. It is applied to quantitative 3D imaging of linear micro-optics.

Fig.2. Prototype of the transmission common-path digital holographic microscope.

Fig.3. Characterization and inspection results of micro-lens array by use of the transmission common-path digital holographic microscope.

Given the refractive index, the geometrical thickness of the lens can be obtained from the quantitative phase map¹¹.

$$h = \frac{\lambda}{2\pi} \frac{\varphi}{(n_L - n_S)} \quad (1)$$

$$ROC = \frac{h}{2} + \frac{D^2}{8h} \quad (2)$$

where h is the height of the microlens; λ is the wavelength of the light; φ is phase measured by SCBS microscope (Phase shift introduced by the microlens); n_L is the refractive index of the lens; n_S is the refractive index of the medium around the test lens. D is the diameter of the microlens. ROC is the radius of curvature of the lens. The measurement results are shown in Fig. 3.

Fig.4. Prototype of the compound common-path digital holographic microscope.

2. Prototype of compound common-path DHM system

A picture of the compound common-path DHM system is shown in Fig.4. It can be applied to quantitative 3D imaging of either transparent object (with good transparency) or opaque object (with good reflection efficiency). When the bottom light source is turning on, the system will work in transmission mode. When the side light source is turning on the system will work in reflection mode.

Fig.5. 3D measurement results of phase film structure by use of the compound common-path digital holographic microscope in transmission mode.

A measurement result of printed phase film by use of the compound common-path DHM prototype in transmission mode (with 10× Olympus MO) is shown in Fig.5. When the system is used in transmission mode, the beam is separated into two parts. One is the object parts and the other is the reference part. This limits the system to small test sample better with areas of gaps between structures. Thus it is very powerful for linear micro-optics. But for the system used in reflection mode, one can take the reference from the same material and get better measurement results as shown in Fig 6 and Fig.7.

Fig.6. 3D measurement results of structures on wafer by use of the compound common-path digital holographic microscope in reflection mode.

Fig.7. 3D measurement results of structures on wafer by use of the compound common-path digital holographic microscope in reflection mode.

4. CONCLUSION

A compound common-path DHM system is build up based on the common-path digital holographic microscopy. The unique way to use the SCBS in the optical path to split and combine the beams enables physical phase compensation of the common-path digital holographic microscopy. Thus the compound digital holographic microscope can work either in transmission mode or in reflection mode. Because the transmission path and the reflection path share the same optical component such as microscope objectives, the cost of the setup is very competitive. Further investigation will focus on the capability of combine the transmission mode and reflection mode to do some measurement of the thickness and refractive index for the transparent object at the same time.

ACKNOWLEDGMENTS

This study is supported by Translational Research & Development grant NRF2009NRF-TRD001-008 from the Singapore National Research Foundation and TIF Fund grant MOE2012-TIF-1-T-003 from the Singapore Ministry of Education.

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