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Capability Enhancement in Compact Digital Holographic Microscopy

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Abstract

A compact reflection digital holographic microscopy (DHM) system integrated with the light source and optical interferometer is developed for 3D topographic characterization and real-time dynamic inspection for Microelectromechanical systems (MEMS). Capability enhancement methods in lateral resolution, axial resolving range and large field of view for the compact DHM system are presented. To enhance the lateral resolution, the numerical aperture of a reflection DHM system is analyzed and optimum designed. To enhance the axial resolving range, dual wavelengths are used to extend the measuring range. To enable the large field of view, stitching of the measurement results is developed in the user-friendly software. Results from surfaces structures on silicon wafer, micro-optics on fused silica and dynamic inspection of MEMS structures demonstrate applications of this compact reflection digital holographic microscope for technical inspection in material science.

Keywords: digital holographic microscopy, resolution enhancement, microelectromechanical systems (MEMS). inspection.

1. INTRODUCTION

3D surface imaging, analysis and metrology system based on reflection digital holographic microscopy (DHM) is attracting more and more attentions from researcher and manufactures^[1,2]. The technique can provide both static imaging and real-time dynamic inspection for samples such as Microelectromechanical systems (MEMS)^[3]. To avoid the optical aberration from the using lens, lensless DHM system is much preferred with compact and simple design. A compact handheld DHM system developed by NTU is reported promise applications in microtechnology, MEMS inspection and semiconductor surface imaging^[4, 5]. Our lensless compact DHM system is based on this previous development. We integrated a diode laser source and maintain the compactness of the system. We have tried several ways to enhance the system resolution: using shorter wavelength, improve the numerical aperture of the system and using a CMOS camera with smaller pixel size. We developed software to enable the stitching of the measurement results for a large field of view inspection. To further develop the axial resolving range, dual wavelengths method is studied to extend the measuring range.

2. PRINCIPLE OF REFLECTION LENSLESS DIGITAL HOLOGRAPHIC MICROSCOPY

2.1 Digital in-line holographic microscopy

In digital in-line holographic microscopy^[6], as shown in Fig.1, a spherical wave of wavelength λ emitting from a point source, illuminates an object, typically a distance a few thousand wavelengths from the source, and forms a highly magnified diffraction pattern on a screen much farther away. The diverging spherical wave can provide a geometrical magnification as compared with plane wave illumination^[7], as shown in Fig. 2. The magnified in-line digital hologram is reconstructed with more details of the object under test.

Fig. 1: Digital in-line holographic microscopy.

Fig. 2: Comparison of the diffraction patterns between spherical wavefront and plane wavefront diffracted by a circular aperture.

Fig. 3: Comparison of the resolution difference between light source with different size and wavelength.

The resolution of the reconstructed in-line hologram depends on several controllable factors or parameters. The first is the size of the point source (or pinhole), controlling spatial coherence and illumination cone. The second is wavelength

in use. As shown in Fig. 3, point sources with different sizes and wavelength will provide different image resolution. Fig. 3 (a) is the in-line hologram for a plant cell obtained from a 5 μm fiber laser point with wavelength 632.8nm. Fig. 3 (c) is the in-line hologram for the same plant cell obtained from a pinhole with 1 μm in size and 405nm in wavelength. The reconstructed image is shown in Fig. 3 (b) and (d). The smaller pinhole size and shorter wavelength gives higher resolution. The third factor is the numerical aperture, given by the size and positioning of the recording CCD chip. The relation between them is

$$NA = \sin \theta = \frac{L/2}{\sqrt{\left(\frac{L}{2}\right)^2 + (D + d)^2}} \quad (2.1.1)$$

Where L is the screen width of the CCD chip, D is the distance between the point source and object, and d is the distance between the object and the CCD chip. The lateral resolution (the minimum distance to which the system distinguishes two neighboring points) is related with NA as follows:

$$\sigma = \frac{\lambda}{2 \cdot NA} \quad (2.1.2)$$

From the above equations, we know that a big CCD chip and a compact recording configuration are needed to improve the resolution of the whole system. The fourth factor is the pixel density and dynamic range, controlling fringe resolution and noise level in the hologram. This depends on the CCD or CMOS camera manufacturing techniques. Currently we are using a CMOS camera with 2.2 μm pixel in size and 2592 $\times$ 1944 in resolution.

2.2 Reflection lensless digital holographic microscopy

Fig. 4: Reflection lensless DHM system.

Reflection lensless digital holographic microscopy system^[4] uses spherical diverging illumination on the object as the same as digital in-line holographic microscopy to achieve the magnified image. It also introduced a reference beam

through a reflection mirror to form an off-axis hologram. Thus it can provide intensity as well as phase information of the test object.

Fig. 5: (a) Reflection lensless DHM system and (b) the system resolution.

The schematic of the reflection lensless DHM system is shown in Fig.4. The laser beam is focused through an objective lens to the pinhole ($1\mu\text{m}$ in size) serving as the point source. A beam splitter cube is used for splitting the diverging spherical wave into two waves. One wavefront is directed to the sample and reflected from the top surface as the object wave. The other is directed to the reflection mirror and reflected as the reference wave. Then, the two waves are recombined by the beam splitter cube to form a hologram. The reflection mirror keeps a slight tilt angle to generate an off-axis digital hologram.

Digital focusing is needed in the hologram numerical reconstruction to achieve the image. The ratio of the distances from point source to digital camera and from point source to sample defines the geometrical magnification of the system. This system presents lensless reflection microscopy geometry by using a very simple and compact optical set-up best suited for the study of samples in tens of microns.

The compact handheld DHM system developed by NTU is able to resolve the group 5 element 6 of the USAF target (about $10\mu\text{m}$).

3. CAPABILITY ENHANCEMENT IN COMPACT DIGITAL HOLOGRAPHIC MICROSCOPY

Capability enhancement methods in lateral resolution, axial resolving range and large field of view for the compact DHM system are introduced in this section. To enhance the lateral resolution, the numerical aperture of a reflection DHM system is analyzed and optimum designed. To enhance the axial resolving range, dual wavelengths are used to extend the measuring range. To enable the large field of view, stitching of the measurement results is developed in the user-friendly software. Results from surfaces structures on coating film demonstrate applications of this compact

reflection digital holographic microscope for technical inspection in material science. Based on the above system we did the following redesign of the CDH system.

For the convenient of using, the laser source is integrated with the CDH system while maintain the compactness of the system. The working distance of the system is extended to 10mm while maintain the same and even higher system resolution. The distance between the beam splitter cube and the test sample d_s is set the same as the distance between the beam splitter cube and the reflection mirror d_M to ensure there is no spherical wavefront difference between the object wavefront and the reference wavefront. To improve the system resolution, two ways are used. One way is using a light source with shorter wavelength to improve the resolution. The other way is by redesigning the light path to provide a bigger NA as shown in Fig.6 to improve the resolution. The point source is relocated inside the beamsplitter by using a lens. The distance between the point source and the sensor of the CCD defines the NA of the system as indicated by Equation (2.1.1). As shown in Fig. 7, from right to left, the resolution is improved while the view field is lost.

Fig. 6: Redesigned NA of the DHM system.

Fig. 7: Resolutions upon different NAs.

The redesigned reflection lensless DHM system and its system resolution are shown in Fig. 8. It is able to resolve the group 7 element 3 of the USAF target (about $4\mu\text{m}$). It can be applied to measure the 3D depth, height and shape of the structures on wafer or other materials with suitable reflectivity. Some measurement results on film coating structures are shown in Fig.9.

Fig. 8: (a) Redesigned reflection lensless DHM system and (b) the system resolution.

Fig. 9: Measurement results for structures on film coating surfaces and wafer.

The phase imaging by digital holography allows sub-wavelength resolution. However for axial ranges greater than one wavelength the phase image has 2π ambiguity and is therefore unable to distinguish points that are separated by an axial distance that is a multiple of the wavelength. So the measurement wavelength must be long enough to cover the range required to avoid 2π ambiguity. However, the longer the wavelength, the lower the resolution. It is desirable to measure height variations at a much longer wavelength than that of the laser while still maintaining the lateral resolution of the shorter laser wavelength. This can be accomplished by separately acquiring the phase data at two or more wavelengths and then looking at the difference of the phase measured by each wavelength. In our system, dual wavelengths are used to extend the measuring range to enhance the axial resolving range from a few nanometers to a few microns, as shown in Fig.10

Fig. 10: Measurement results by dual-wavelength method.

The stitching of the measurement results is developed in the user-friendly software to enable the large field of view inspection, as shown in Fig.11;

Fig. 11: Measurement result for stitched view field^[8].

As a conclusion, we demonstrate the enhanced capability of the lensless digital holographic microscopy system. The

lateral resolution is improved from 10 μm to 4 μm by using a shorter wavelength and a bigger NA. The measurement range is extended from a few nanometers to a few microns by using dual-wavelength method. The view field is also enlarged by phase stitching method. We also integrated the laser source together with the optical interferometer to make the system portable as well as easy in use.

4. ACKNOWLEDGEMENTS

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