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Three-dimensional imaging of microstructures by an improved compact digital holographic microscope (ICDHM) with dual wavelength

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Abstract

An improved compact digital holographic microscope (ICDHM) is developed for three-dimensional imaging of microstructures. This system is based on lensless magnification using a diverging wave. A point source generated by a long working distance microscope objective is located into the cube beam-splitter to get a higher numerical aperture (NA) of the system. The lateral resolution and the field-of-view of the system are confirmed with a calibration experiment. For the case of the optical path lengths (OPL) of object with step pattern larger than the wavelength, the traditional phase unwrapping algorithms cannot be unequivocally determinate, resulting in a 2π phase ambiguity. To solve this problem, dual wavelength phase unwrapping method was integrated into ICDHM, which extends the measuring capability of ICDHM over several microns of range. The experimental results demonstrate that the developed system is well suitable for the measurement of MEMS and Micro systems samples with high resolution.

Keywords: Digital holography microscopy; dual wavelength; Three-dimension measurement; MEMS.

1. INTRODUCTION

Digital holography (DH) has emerged as a powerful technique for study of 3D structure of microscopic objects due to the quantitative amplitude and phase information can be obtained by numerical reconstruction of the hologram [1-3]. Development of optical tools for on-line inspection and characterization of micro-devices, e.g. Microelectromechanical systems (MEMS), are highly demanding and a challenging task. For this reason, a compact handheld digital holographic microscope (CDHM) system is developed by A. Asundi et al [4, 5], applications in micro-technology, MEMS inspection and semiconductor surface imaging. Recently, we presented an integrated lensless compact DHM system with a shorter laser wavelength to enhance the system resolution [6]. However, for quantitative phase measurement, phase maps calculated with the *arctan* function or other inverse trigonometric functions therefore contain 2π jumps at those positions. Therefore, most phase unwrapping algorithms [7-9] are used to retrieve the true continuous phase map of object. However, for the optical path lengths (OPL) of object with step pattern larger than the wavelength of the illumination light, those phase unwrapping algorithms cannot be unequivocally measured, resulting in a phase ambiguity. In addition, phase unwrapping methods are often time-consuming and this will reduce the speed of real-time measurement. To overcome this problem, dual wavelength method was proposed [10-12], which offers a method that is fast, efficient, and deterministic. In dual-wavelength phase unwrapping method, two wavelengths are used to produce a longer wavelength called the 'beat wavelength'. By choosing two suitable wavelengths, the beat wavelength can be extended in the range of 2π discontinuities in the phase map.

In this paper, an improved compact digital holographic microscope (ICDHM) with dual wavelength is proposed, which enhances the lateral resolution of system as well as provides the system with the capability of measuring over a range of step heights from dozens of nanometers to several micrometers realm. The analysis and experimental results show the validity of this method.

2. BASIC PRINCIPLE

2.1 Improved compact digital holographic microscope (ICDHM)

The schematic of the reflection lensless CDHM system introduced in reference [4] is shown in Fig.1(a). The laser beam is coupled into a fiber and the fiber end as the point source produces a diverging spherical wave. 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 its surface as the object wave. The other is directed to the reflection mirror and reflected as the reference wave. Then, the object and reference 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. As we all know, to improve the lateral resolution two parameters can be manipulated. Firstly, the wavelength has to be reduced to optimize the lateral resolution. Secondly, the NA value has to be as high as possible. Here the NA of system is defined as follows:

$$NA = \sin \theta = \frac{m/2}{\sqrt{\left(m/2\right)^2 + (D+d)^2}} \quad (1)$$

where m 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.

Fig.1 Two configurations: (a) CDHM; (b) ICDHM.

When the distance d is fixed, there is a disadvantage of this kind of system is that D cannot be further reduced to increase the NA due to the existence of the beam splitter. Here, we presented an ICDHM configuration, as shown in Fig.1(b), which is based on the configuration of Fig.1(a). The biggest difference between Fig.1(a) and Fig.1(b) is that the diverging laser beam from fiber end in Fig.1(b) is incident on a converging lens to produce a point source, which locates inside the beam splitter. Thus the distance D between the point source and the sensor of the CCD is reduced while the NA value is increased as indicated by Equation (1). Note that the resolution is improved while the field of view (FOV) is lost. Here the distance between sample and CCD is about 45mm. Then the magnification of this system can be calculated which is about 4X and FOV is about 1.2mm². Fig.2 shows the lateral resolution with different configuration as shown in Fig.1.

Fig.2 System resolution with different configurations: (a) CDHM; (b) ICDHM.

2.2 Dual wavelength technology in ICDHM

Fig.3 The sketch map of dual wavelength ICDHM setup.

Fig.3 shows the sketch map of dual wavelength ICDHM setup. Two laser sources with different wavelengths are coupled into an optical fiber coupler simultaneously. In dual wavelength digital holography, two individual holograms need to be recorded by using different wavelengths. Here the fiber coupler is switched to let the beam of laser 1 or laser 2 pass through. Thus two digital holograms with different wavelengths are recorded, respectively.

For wavelength λ_i , the intensity of digital hologram recorded by CCD is

$$I_i = |R_i|^2 + |O_i|^2 + R_i O_i^* + R_i^* O_i \quad (1)$$

where R_i and O_i are the reference and object waves for the wavelength λ_i , respectively. In off-axis digital holography, the zero order and the virtual image can be easily separated from the real image in frequency spectrum of Fourier transform. Here real image term is selected with a numerical band filter and then it can be numerical reconstructed by the angular spectrum formulation [5]:

$$U_i = F^{-1} \left\{ F \{ R_i \cdot I_i \} \cdot \exp \left[j \frac{2\pi}{\lambda_i} d_i \sqrt{1 - (\lambda_i f_x)^2 - (\lambda_i f_y)^2} \right] \right\} \quad (2)$$

where F and F^{-1} denote Fourier transform and inverse Fourier transform operation, U_i is the reconstructed complex amplitude of the object wavelength and d_i is the reconstruction distance for λ_i . For the reflection sample, the phase Φ of sample for the beat wavelength Λ can be written as

$$\Phi = \arg(U_1 U_2^*) = \varphi_1 - \varphi_2 = \frac{2\pi L(h)}{\lambda_1} - \frac{2\pi L(h)}{\lambda_2} = \frac{2\pi L(h)}{\Lambda} \quad (3)$$

where $L(h)$ is the optical path length (OPL), $\Lambda = |\lambda_2 - \lambda_1|/\lambda_1 \lambda_2$ and φ_i is the reconstructed phase with wavelength λ_i . The phase image Φ for beat wavelength is obtained by subtracting phase image φ_1 from φ_2 and then just adding 2π whenever the resultant value is less than zero. When the OPL in measurement is shorter than beat wavelength, there will not be phase ambiguities. So this technique can resolve much higher structures by selecting two appropriate laser sources.

3. EXPERIMENTAL RESULTS

In this experiment, the sample tested is a wafer with a square step microstructure on the surface. The 2D profile of the sample measured by Bruker Dektak XT contact profilometer (vertical resolution is 0.1nm) is shown in Fig.4, the average height is 14.1656um.

Fig.4 Result obtained by the Bruker Dektak XT: (a) live video; (b) 2D height data analysis.

With our method, the experimental setup as shown in Fig.3. In order to avoid the phase ambiguities, the two diode lasers with the wavelength 654.3nm and 660nm are used and calibrated as the light sources, which the beat wavelength is 75.76um. The two digital holograms recorded independently by ICDHM system with different wavelengths are shown in Fig.5(a) and Fig.5(b). The holograms are reconstructed by angular spectrum method and their wrapped phase maps are shown in Fig.5(c) and Fig.5(d), respectively. Here, dual wavelength technique as we discussed in section 2.2 is carried out to obtain the continuous phase of sample. Fig.6(a) and Fig.6(b) show the 2D and 3D maps of dual wavelength phase unwrapping result, respectively. Fig.6(c) and Fig.6(d) are the 2D profiles of the sample along the solid line and dash line in Fig.6(a). This height result is agree well with the result shown in Fig.4.

Fig.5 Result: (a) digital hologram and its wrapped phase map (c) with $\lambda_1 = 654.3\text{nm}$; (b) digital hologram and its wrapped phase map (d) with $\lambda_1 = 660\text{nm}$.

Fig.6 Results of dual wavelength unwrapping: (a) 2D map; (b) 3D map; (c) the profile of the sample along the solid line in (a); (d) the profile of the sample along the dash line in (a).

4. CONCLUSIONS AND DISCUSSIONS

In this paper, we proposed an ICDHM system to enhance the lateral resolution. This system is based on lensless magnification using a diverging wave. A point source generated by a long working distance microscope objective is located into the cube beam-splitter to get a higher NA value of the system. The lateral resolution of the system is up to 4 micros. To enhance the axial resolving range, dual wavelength phase unwrapping method was integrated into ICDHM, which extends the measuring capability of ICDHM over 70 microns of range. By using dual wavelength method, the beat wavelength is much larger than any single wavelength and this extends the capability of measuring step samples. However, the noise or system error in the original phase images is magnified by the same factor as beat wavelength at the same time [13], which decreases the vertical accuracy, as shown in Fig.7. To overcome this issue, many researchers have studied on this topic [14-16]. This work will also be studied in our future work.

Fig.7 2D profile results of a flat mirror obtained from (a) dual wavelength (beat wavelength is 75.76um) method and (b) single wavelength (660nm) method.

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