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Phase Shifted Photomask Inspection by Digital Holography Microscope

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Abstract

We present a digital holography microscope and reconstruct the intensity and phase image of fully transparency object. The phase aberration is corrected by using a digital correction method. We can obtain complete three-dimensional information on the object by using the intensity, the phase, and an unwrapping algorithm. Also we have demonstrated this system could detect defect in phase shift photo-mask and visualize the 3-dimensional images of defects.

Keywords : Optics, Image reconstruction, Image Processing

Ⅰ. INTRDUCTION

Holography, a photographic technique designed by Dennis Gabor in late 1940s, is a method of recording the phase modulation from the light reflected or transmitted from a projected object to a photo-plate in the form of interference pattern. For recording, an object beam and a reference beam are required, and as the result of combining two beams, an interference pattern is made. In the past, the interference patterns were recorded on a film plate. However, computers are now widely used in recording and reconstructing hologram thanks to the rapid development of computer technology. Yaroslavskii et al. firstly proposed a hologram reconstruction in numerical values in 1970s [1-3], and Ounral and Scott used the numerical reconstruction into measuring a particle size after improving reconstruction algorithm [4-7]. However, the entire recording and reconstructing of hologram had not been digitalized yet. Schnars and Juptner presented a direct method of recording a Fresnel hologram with a charged coupled device (CCD) and then reconstructing it numerically [8, 9]. Such a way of digitally recording and reconstructing a numerical hologram was called digital holography ever since. Digital holography has many advantages: no chemical or physical development process is required, the reconstruction image can easily be observed on a computer screen, the visualization of transparent objects is possible, and numerical data for the three-dimensional shapes of objects are obtained. However, the resolution is one order of magnitude less than that of standard film holography. The resolution of a CCD is ~100 lines/mm. However, using CCD's for recording holograms is advantageous because video frequencies are available. An example of digital holography is a digital holographic microscope that measures micro particles in a three-dimensional system. Generally a digital holographic microscope is divided into those with an object lens [10,11] and without an object lens [12]. When using an object lens, a CCD is placed between the image forming position and object lens to recording. Cuche et al. presented a digital holographic microscope that had the ability to reconstruct an amplitude and quantitative phase contrast image and the ability to provide precise quantitative information about the three-dimensional structure of the object by computational means with a single hologram [10]. With the digital technology this opens up many possible applications, including metrology and defect inspection for semiconductor process diagnostics. One immediate and important application that has been under development is the inspection of semiconductor wafers, and in particular the inspection of high aspect ratio structures and also of defects that present themselves as phase objects, where other optical inspection techniques have considerable difficulty in achieving a reasonable defect signal, or any signal at all [13,14].

In this study, off-axis holograms are recorded and numerically reconstructed by calculating the scalar diffraction in the Fresnel approximation. We will demonstrate that the phase image and contrast image reconstruction is possible and digital holography could detect the phase defect in phase shift photo-mask.

Ⅱ. Theoretical Model

1. Hologram Recording

Figure 1 shows the recording geometry. A plane reference wave (R) and a diffusively reflected object wave (O) interfere at the CCD. The hologram intensity is given by

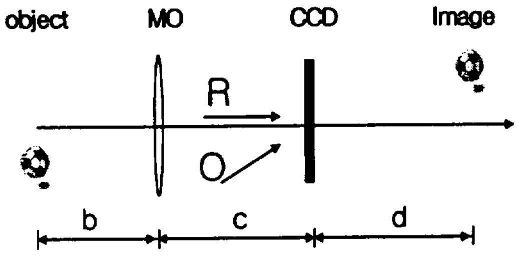


Fig. 1. Off-axis recording holography with a plane reference wave. MO: magnification lens, R: reference wave, O:object wave, b: distance between object and lens, c; distance between CCD and lens, d; distance between CCD and reconstruction plan

$$I_H(x,y) = |R|^2 + |O|^2 + R^*O + RO^* \quad (1)$$

where R^* and O^* denotes the complex conjugates of the reference wave and the object wave, respectively. The digital hologram image can be recorded at standard a black and white CCD camera. The digital hologram $I_H(k,l)$ is the $N \times N$ array resulting from the two-dimensional sampling of $I_H(x,y)$ by the CCD camera:

$$I_H(k,l) = I_H(x,y) rect\left(\frac{x}{L},\frac{y}{L}\right) \times \sum_{k=-N/2}^{N/2} \sum_{l=-N/2}^{N/2} \delta(x - k\Delta x, y - l\Delta y) \quad (2)$$

where k,l are integers, $L \times L$ is the area of the CCD chip, and $\Delta x, \Delta y$ defines the pixel size of the CCD.

2. Hologram Reconstruction

In classical optical holography the object wave can be reconstructed by illumination of the processed hologram with a plane wave, similar to that used in the process of recording. Looking through the hologram, we observe a virtual image. If a screen is placed at a distance d behind the hologram, a real image is formed. Mathematically the amplitude and phase distribution in the plane of the real image can be found by using the Fresnel-Kirchhoff integral. If a plane wave illuminates the hologram with an amplitude transmittance $I_H(x,y)$, the Fresnel-Kirchhoff integral results in a complex amplitude, $\Psi(\xi,\eta)$, in the plane of the real image:

$$\Psi(\xi,\eta) = \frac{\exp(i2\pi d/\lambda)}{i\lambda d} \exp\left[\frac{i\pi}{d\lambda}(\xi^2+\eta^2)\right] \times \iint I_H(x,y) \exp\left[\frac{i\pi}{d\lambda}(x^2+y^2)\right] \times \exp\left[\frac{i2\pi}{d\lambda}(\xi x+\eta y)\right] dxdy \quad (3)$$

where λ is the wavelength and d is the reconstruction distance. From Eq. (3), the Fresnel-Kirchoff integral can be viewed as a Fourier transformation in the spatial frequencies ξ and η of the function $I_H(x,y)\exp[\,i\pi(x^2+y^2)/\lambda d\,]$. For rapid numerical calculation, a discrete formulation of Eq. (3) involving a two-dimensional fast Fourier transformation can be derived directly:

$$\Psi(m,n)=\frac{\exp(i2\pi d/\lambda)}{i\lambda d}\exp[\frac{i\pi}{d\lambda}(m^2\Delta\xi^2+n^2\Delta\eta^2)]$$
$$\times FFT\{I_H(k,l)\exp[\frac{i\pi}{d\lambda}(k^2\Delta x^2+l^2\Delta y^2)]\}_{m,n} \quad (4)$$

where k,l,m,n are integers $(-N/2\leq k,l,m,n\leq N/2)$.

The values of the sampling intervals in the observation plane $(\Delta\xi,\Delta\eta)$ can be deduced directly from $\Delta\xi=\Delta\eta=\frac{\lambda d}{N\Delta x}=\frac{\lambda d}{L}$. Normally, a lens produces a curvature of the wave front in the object arm. The deformation affects only the phase of the object wave and does not disturb the amplitude-contrast imaging. However, for phase contrast imaging, the phase aberration must be corrected, and many methods have been presented to correct the phase aberration [9, 15-18]. One of them uses digital correction. This does not require optical components. After phase correction with a digital method, the complete expression of the reconstruction function becomes [10]

$$\Psi(m,n)=\frac{\exp(i2\pi d/\lambda)}{i\lambda d}\exp[\frac{i\pi}{d\lambda}(m^2\Delta\xi^2+n^2\Delta\eta^2)]$$
$$\times FFT\{R_D(k,l)I_H(k,l)\exp[\frac{i\pi}{d\lambda}(k^2\Delta x^2+l^2\Delta y^2)]\}_{m,n},$$
$$R_D(k,l)=\mathrm{Re}(\frac{\exp(i2\pi d/\lambda)}{i\lambda d})$$
$$\exp[i(2\pi/\lambda)(k_x k\Delta x+k_y k\Delta y)] \quad (5)$$

where k_x,k_y are the wave vectors and $R_D(k,l)$ is the digital reference wave. In digital holography, the digital hologram should be multiplied by the digital reference wave R_D, which must be a replica of the experimental reference wave R. Since $\Psi(m,n)$ is an array of complex numbers, we can obtain an amplitude-contrast image by using the intensity

$$I(m,n)=\mathrm{Re}[\Psi(m,n)]^2+\mathrm{Im}[\Psi(m,n)]^2 \quad (6)$$

and a phase-contrast image by calculating the argument

$$\phi(m,n)=\arctan\{\frac{\mathrm{Im}[\Psi(m,n)]}{\mathrm{Re}[\Psi(m,n)]}\} \quad (7)$$

The reconstruction function $\Psi(m,n)$ involves reconstruction parameters and the reconstruction distance (d) for the calculation of the reference wave vectors (k_x,k_y). These reconstruction parameters represent the physical geometry (distances and angles) and can be measured experimentally.

Ⅲ. EXPERIMENT

As Fig. 2 shows, the major equipment of experiment was a Mach-Zehnder type interferometer. The beam source is a CW He-Ne laser with a wavelength of 632.8 ㎚, the height and left/right direction is modulated with mirrors M1 & M2, and the beams are divided into two by using beam

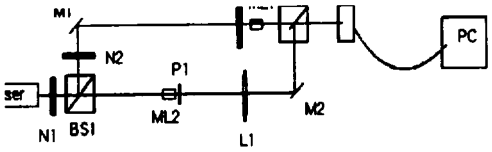
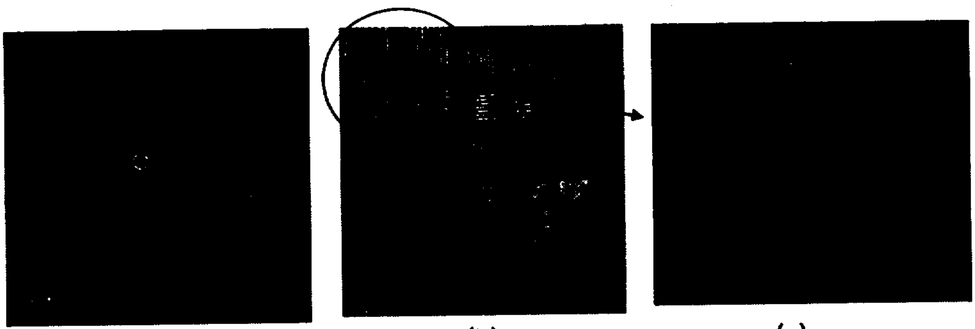


Fig. 2. Schematic diagram of digital holography microscope. M1, M2 : mirrors, N1, N2 ; Neutral density filters, ML1, ML2 ; micro lenses, L1; lens, P1; Pin hole, BS1, BS2 ; Beam Splitters.

splitter (BS1). The beam that passes through BS1 is used as the object beam, and the reflected beam is used as the reference beam. Neutral density filters, N1 and N2, are used to achieve a hologram with maximum diffraction efficiency by controlling the brightness of the object beam and the reference beam. The reference beam is prepared as a parallel beam via a lens (L1) by using an object lens (ML2) and a pinhole (P1) to get as close as possible to the TEM00 mode of a Gaussian beam. We used the transmitted line and space phase shift photo mask pattern for samples. The object lens for forming the image is of 100× (N.A. =0.9) from Mitutoyo company. The CCD is MegaplusII from Kodak with resolution of 2048×2048 and pixel size of 7.4㎛×7.4㎛. We tilted the mirror M3 to record the holograms in an off-axis geometry. The reference wave reaches the CCD camera with a small incidence angle with respect to the propagation direction of the object wave. We fixed the incident angle at 2.46 degree. We prepared the phase shift photo-mask for sample. The periods of pattern are varied from 0.8㎛ to 2㎛ and the depth of patterns are varied from 200 nm to 800 nm.

Ⅳ. Results

Figure 3 shows the experimental result for non-defect phase shift photo-mask. Figure 3(a) is the hologram image of mask pattern. We can see in Fig. 3(a) that

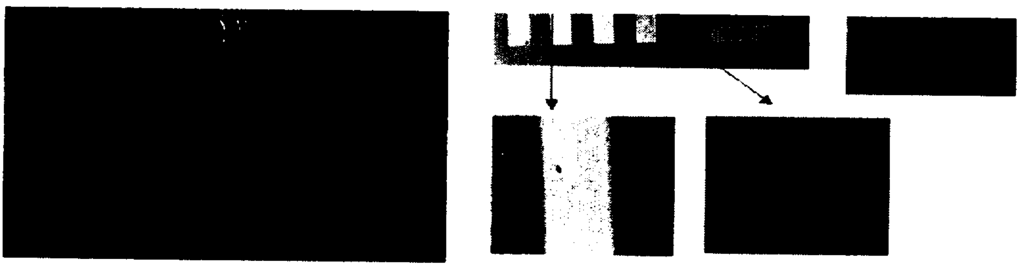


(a) (b) (c)

Fig. 3. Results for phase shift photo-mask. The distance from CCD to reconstructed plane is 60 cm. (a) hologram, (b) phase image, (c) 3-dimensional image

the hologram appears as a pattern of interference fringes. The fringes are caused by phase aberration produced by the objective lens, which is the system noise. To increase the image quality of object we discard this system noise by substrate the system hologram from object hologram. We fix the reconstruction distance (*d*) as 60 ㎝ from CCD. We use the Fresnel-Kirchoff transform to acquire the reconstructed image. The corresponding reconstructed phase-contrast image is represented in Fig. 3(b). The normal microscope cannot visualize this image since the phase photo-mask is fully transparence and without chrome. Fig. 3(c) is the 3-dimensional image, which are reconstructed by phase unwrapping. From this experimental result we found that digital holography microscope could reconstruct the 2-dimensional contrast image and 3-dimensional image of phase shift photo-mask simultaneously. Normal microscope could not image the phase shift photo-mask.

We prepared the defect phase shift photo-mask by deposit the sub-micro polystyrene bead to non-defect sample. Figure 4 shows the experimental result for defect photo-mask. In Fig. 4(a) we show the hologram of defect photo-mask and corresponding reconstructed phase-contrast image is represented in Fig. 4(b). The defects in phase shift photo-mask are visualized well. From these results we can verify that digital holography microscope is useful technique for detecting the defect of transparency object, phase shift photo-mask. Also we reconstructed the 3-dimension defect image and are in Fig. 5. These results show that the digital holography microscope is useful technique



(a) (b)

Fig. 4. Results for defect phase shift photo-mask. (a) hologram, (b) phase image and enlarged the defect image

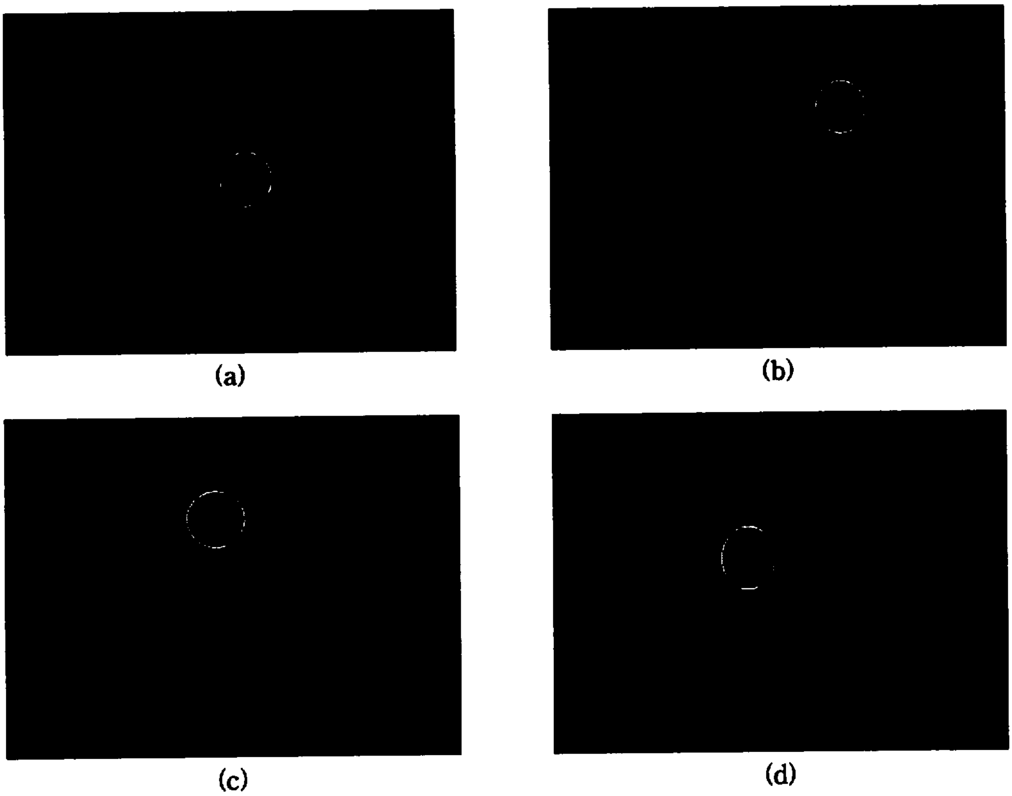


Fig. 5. 3-dimension defect image. (a), (b), (c), (d) corresponding to 1), 2), 3), 4) in figure 4.

for identify the defect shape. We can observe some small spots in Fig. 4 and Fig. 5. These spots are noises of CCD pixels. These system noises, including the lens aberration and optical detector noise, should be removed to increase the defect detecting power. We will make efforts to increase the detecting power by decrease the system noise in future study.

V. CONCLUSION

The digital holography microscope system described in this paper permits two-dimensional and three-dimensional imaging of fully transparency object. An object lens in a digital holography microscope system induces phase aberration. To correct the phase aberration, we use a digital correction. The information on the complete three-dimensional image is obtained by using intensity and phase information and a phase unwrapping algorithm. An attractive feature of this system is that precise quantitative information about the three-dimensional structure of an object can be obtained by using only one hologram. Also we verify that the digital holography microscope is useful technique for detecting the defect of transparency object, phase shift photo-mask. This system can be applied in semiconductor inspection area. However, there are many error sources, which decrease the defect detecting power of system. We should remove the system noise for useful inspection system.

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