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Development of a simple user-friendly commercial digital holographic microscope

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ABSTRACT

We report the development of a simple commercial digital holographic microscope. The hologram is recorded using a CCD sensor and numerically reconstructed to provide quantitative analysis of the object. The laser source is coupled via fibre optics and the opto-mechanical setup is flexible and customizable for either the reflection or transmission mode. The user-friendly software allows live reconstruction, simultaneously providing both the amplitude and phase images. System performance is improved with phase unwrapping and interferometric comparison. Additional features include various image enhancements, cross-sectional and line profiling, measurement and data analysis tools for quantitative 3D imaging and surface topography measurement. The performance of the product is tested on different micro devices, glass and silicon surfaces.

Keyword: Digital Holography, Phase Measurement, 3D Imaging

1. INTRODUCTION

The direct recording of holograms with a CCD sensor was first reported by Schnars and Juptner¹. Digital holograms offer many advantages not afforded by classical ones since they can be numerically reconstructed to provide, not only the intensity image but also, the phase contrast image. Digital holography, thus, enables the quantitative measurement and analysis of the recorded object.

The principles and applications of digital holography have been extensively described²⁻⁴. Here, we report the development of a simple low-cost commercial digital holographic microscope (DHM). The setup is flexible and customizable for either the reflection or transmission mode. The user-friendly software allows live reconstruction providing the intensity and phase images, and the 3D perspective. The performance of the product is tested on different micro devices, glass and silicon surfaces.

2. DESCRIPTION OF SYSTEM

Figure 1a shows the DHM setup based on the Michelson interferometer and configured for reflection mode. The laser diode source is coupled via fibre optics to a collimator. The collimated beam is splitted into two parts for the reference and object beams. The latter is reflected from the sample and interferes with the reference beam at a small off-axis angle. The resulting hologram is captured by a CCD camera.

Each component of the system is modularized and can be reconnected for transmission mode as shown in Figure 1c. The system also has the option to include a microscope objective for applications with smaller features to be imaged and measured. Figure 1b shows a packaged reflection DHM developed for the characterisation of microelectronics and MEMS devices.

Figure 1. DHM setup (a) Reflection mode (b) Packaged system (c) Transmission mode

The hologram acquired by the CCD sensor has an intensity

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

where the first two terms are the intensity of the reference and object waves or zero-order of diffraction, and the last two terms correspond to the interference between the object wave or its conjugate and the reference wave.

Figure 2 shows these terms in the Fourier domain. The real or virtual image can be selected for reconstruction while eliminating the other and zero-order terms. The filtered term $(H(x, y))$ is then numerically propagated with the appropriate reconstruction distance to obtain the complex wavefront $U(x', y')$ using the Fresnel diffraction equation,

$$U(x', y') = \frac{e^{ikd}}{i\lambda d} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} H(x, y) R(x, y) \exp\left[\frac{i\pi}{\lambda d} \{(x' - x)^2 + (y' - y)^2\}\right] dx dy \quad (2)$$

Where $k = \frac{2\pi}{\lambda}$, is the wave number and d is the reconstruction distance.

Figure 2. Real or virtual image selectable for reconstruction from Fourier domain

The amplitude and phase contrast images can then be calculated from

$$I(x', y') = |U(x', y')|^2 \quad (3a)$$

$$\varphi(x', y') = \arctan\left[\frac{\text{Im}(U(x', y'))}{\text{Re}(U(x', y'))}\right] \quad (3b)$$

The phase distribution in reflection mode is directly related to the height distribution by

$$h = \frac{\varphi\lambda}{4\pi} \quad (4)$$

3. EXPERIMENTAL RESULTS

The DHM was applied in the 3D imaging and measurement of different objects to characterise its performance. The user-friendly software allows digital focusing and live reconstruction of the holograms, displaying the intensity image, phase contrast, and 3D perspective.

Figures 3 and 4 show the phase contrast image with an analysis of the cross-section profile and depth measurement of MEMS and silicon devices.

Figure 3. MEMS device (a) Phase image and cross-section profile (b) 3D perspective

Figure 4. Silicon etch (a) Phase image and depth measurement (b) 3D perspective

In Figure 5, a semiconductor device whose surface shows warpage and is detached from the adhesive bond was inspected. The intensity image (Figure 5e) did not show the warpage revealed by the phase image shown in the 3D representation (Figure 5f).

Figure 5. Semiconductor device warpage (a) Modulo-2 π phase image (b) Wrapped phase profile (c) Unwrapped phase image (d) Surface profile (e) Amplitude image (f) 3D perspective

The characteristics of a glass slide marked by a CO₂ laser was also investigated (Figure 6).

Figure 6. CO₂ laser mark on glass slide (a) Phase image and surface profile (b) 3D perspective

Interferometric measurements with the system were also performed. The deformation of a piezo-actuated MEMS diaphragm was studied when a voltage was applied. Figure 7a shows the amplitude-reconstructed image of the MEMS diaphragm. For interferometric measurements, a reference hologram was first recorded when no voltage was applied. The phase subtraction of the reference hologram from the deformed hologram provides the deformation fringes. Figures 7b, 7c and 7d show the deformation fringes when the applied voltage was increased to 5 volts, 6 volts and 7 volts.

(a)

Figure 7 Deformation of piezo-actuated MEMS diaphragm (a) Amplitude image
(b)-(d) Deformations fringes corresponding to applied voltage of 5 volts, 6 volts, and 7 volts respectively

4. CONCLUSION

We have developed a low-cost DHM with modular parts which permit us to easily set up and customise the system and processing software for either the reflection or transmission mode and to include flexible options for different applications. The software allows live reconstruction, providing both the amplitude and phase images, for quantitative 3D imaging and surface topography measurement. The performance of the product has been applied to various micro devices, glass and silicon surfaces.

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