Wavelength-Tuning Common-Path Digital Holographic Microscopy for Quantitative Phase Imaging of Functional Micro-Optics Components

Bingcai Liu 1,*, Dasen Wang 2, Xueliang Zhu 1, Hongjun Wang 1, Ailing Tian 1 and Weiguo Liu 1

1 Shaanxi Province Key Lab of Thin Films Technology and Optical Test, Xi’an Technological University, Xi’an 710021, China; zhuxueliang@xatu.edu.cn (X.Z.); whj0253@sina.com (H.W.); ailintian@xatu.edu.cn (A.T.); wgliu@163.com (W.L.)
2 Ningbo Branch of China Academy of Ordnance Science, Ningbo 315103, China; wds9059@163.com
* Correspondence: liubingcai@xatu.edu.cn

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Abstract: This study proposes a novel wavelength-tuning common-path digital holographic microscopy technique for quantitative phase imaging of functional micro-optics components. The proposed technique is immune to vibration and can reduce system error. In the proposed configuration, a parallel glass plate was inserted into the light path to create two identical test beams, which passed through a specially designed window filter. In this process, one beam serves as the object beam, while the other is diffracted to produce an ideal spherical wave front (the reference beam). A wavelength tunable laser was used as the light source to generate phase-shifting digital holograms. Structural information for the functional micro-optics components was then extracted using a classical four-step phase-shift algorithm. The viability of the proposed technique was assessed by measuring a micro-optics array.

Keywords: digital holographic microscopy; phase measurements; wavelength tuning; phase shifting

1. Introduction

Functional micro-optics components (FMOCs) are typically used in the modulation of optical wave fields, digital holographic interferometry, and the measurement of phase or intensity in 3D specimens. The surface of these devices exhibits varying features and diverse combinations of microstructures, which can be used to modulate optical parameters such as phase, amplitude, and polarization. A wide variety of miniature optical instruments, based on FMOCs, has been developed in recent years. For example, micro-lens arrays have been used to measure the slope of wave fronts in Hartmann sensors, a challenging application of phase imaging with FMOCs. Digital holographic microscopy (DHM), a relatively new technique, can measure the amplitude and phase distribution of an objective wave field used to modulate sample data. DHM offers the advantages of full field, noninvasive, high precision, and high-speed imaging. As a result, it has been widely used for micro-lens measurement [1,2], microstructure measurements [3–6], particle tracking [7–9], biological imaging [10–12], and material engineering [13,14].

Conventional DHM systems are based on a Michelson and Mach–Zehnder interferometer. In these configurations, the object and reference beams pass through separated light paths. The primary disadvantage of this approach is the disturbance caused by mechanical vibrations in either of the interferometric arms, which reduces the long-term stability of the device. Novel optical configurations implementing parallel glass plates [11,15], cube beam splitters [16–18], or a Sagnac framework [19,20] have been introduced to resolve problems with instability. This configuration, in which both interference
beams propagate together, is referred to as common-path DHM. Common-path techniques can be divided into two broad categories: in-line and off-axis imaging. In-line holography faces the inevitable problem of a conjugate image and zeroth-order wave being superimposed on the object image, making phase reconstruction difficult. The precision of off-axis holography is reduced by the spectral selection window, which restricts the bandwidth of the frequency spectrum. Phase-shifting digital holography was proposed to resolve this issue [21–26]. In this process, a phase-shifting device, such as a flat mirror mounted to a piezoelectric transducer (PZT), is introduced in the reference arm to shift the phase between the two interference beams. This allows for the recording of multiple phase-shifted holograms, but only the object image can be reconstructed using a phase-shifting technique. A PZT-actuated flat mirror is easily introduced in a Michelson or Mach–Zehnder interferometry configuration; however, this requires mechanical movement with high-positioning precision. Wavelength-tuning technology [27–30] can realize phase shifting without mechanical movement when an interference cavity remains constant, Fairman et al. [29] established a 300 mm aperture Fizeau interferometer based on wavelength-tuning technology with repeatability precision of 0.3 nm RMS, and a 610 mm aperture interferometer was developed with residual error of 0.56 nm RMS by the Zygo Corporation [30].

This study introduces a novel wavelength-tuning methodology for the quantitative phase imaging of functional micro-optics components in common-path digital holographic microscopy. With this approach, system errors can be reduced and phase measurement precision can be improved by eliminating mechanical components from the phase-shifting steps. Experimental results demonstrated the proposed technique to be a powerful new tool for DHM imaging.

2. Experimental Configuration and Phase Reconstruction

The proposed configuration for wavelength-tuning common-path DHM is shown in Figure 1. In this process, an adjustable wavelength laser (a NEW FOCUS TLB-6804 series diode-pumped solid-state laser with a central wavelength of 632.85 nm, a wavelength-tuning range of 632.73–632.98 nm, and a frequency stability of 2 pm over 12 h) was coupled with a single-mode fiber using a coupler device (GCX-C18PC-A; Daheng New Epoch Technology, Inc.). The beam was collimated using a fiber collimator (Thorlabs F260FC-B with a design wavelength of 633 nm and a beam diameter of 2.8 mm) prior to illuminating the sample. After passing through a transparent functional microstructure specimen and a 10× microscope objective (NA of 0.25), the beam wave front was modulated by the specimen and separately reflected by the front and back surfaces of a parallel glass plate, producing two divergent beams. The beams were then focused through a lens (focal length, 150 mm) and onto a filter plane composed of two filter windows, as shown in Figure 2. In the figure, the lower window includes a round hole with a 5 mm diameter and the upper window contains a pinhole with a 50 µm diameter. The beam was transmitted through the round hole when the focus point, which is formed by the front surface of the parallel glass plate, matches the lower window and contains a pinhole with a 50 µm diameter. The beam was transmitted through the round hole when the focus point, which is formed by the front surface of the parallel glass plate, matches the lower window. As a result, the wave front exhibits no change and the object wave front is produced. The beam originating from a reflection on the back surface of the parallel glass plate (coated high reflective film) is then focused in front of the filter. This forms a circular spot when the beam reaches the filter plane, which covers the entire pinhole window. The beam then diffracts as an ideal spherical reference wave front. The two waves from the round hole and pin hole filters interfere with each other and form a digital hologram. The corresponding interferogram was recorded by a grayscale CMOS camera (Imaging Source DMK 42AUC03, 1280 × 960 pixels, with a pixel size of 3.75 × 3.75 µm, and an 8-bit dynamic range).
Figure 1. The experimental configuration for wavelength-tuning common-path digital holographic microscopy (DHM).

Figure 2. The window filter design. The upper window is 50 μm and the lower window is 5 mm; the distance is 10 mm.

The wave fronts reflected from the front and rear surfaces of the parallel glass plate interfere with each other at a fixed optical path difference \( \text{OPD} = \frac{2nhd}{\sqrt{n^2 - \sin^2 \theta}} \), which depends on the parallel glass plate thickness \( h \), the refractive index \( n \), and the incident angle \( \theta \), as shown in Figure 3. For \( h = 20 \text{ mm}, n = 1.46 \), and \( \theta = 45^\circ \), the optical path difference (OPD) was 45.72 mm. The resulting phase difference between the two interfering beams \( \varphi \) can then be expressed as:

\[
\varphi = \frac{2\pi}{\lambda} \text{OPD} = \frac{4\pi nhd}{\lambda \sqrt{n^2 - \sin^2 \theta}}
\]

where \( \lambda \) is the centroid wavelength.
The wavelength of the tuning laser can be adjusted linearly from, for example, 632.73 to 632.98 nm. The phase difference will then be an inversely proportional linear relationship relative to the centroid wavelength ($\lambda = 632.85$ nm):

$$\varphi - \Delta \varphi = \frac{2\pi}{\lambda} \text{OPD} = \frac{4\pi n h}{(\lambda + \Delta \lambda) \sqrt{h^2 - \sin^2 \theta}}$$  \hspace{1cm} (2)

The optical path difference between the two interfering beams can be adjusted by using the parallel plate, thus varying the thickness and refractive index. The adjustable phase difference range for the tuning laser will change in response and phase-shifting digital holograms can be captured by the CMOS camera. In addition, the system noise from uncommon path configurations can be theoretically eliminated as the object and reference wave fronts pass through the same point in the experimental setup. This approach to high-precision phase-shifting holography, without mechanical components, could reduce the vibration influence during holographic phase reconstructions.

The object and reference waves can be represented by:

$$O(x, y) = o(x, y) \exp[-j\varphi_o(x, y)]$$
$$R(x, y) = r(x, y) \exp[-j\varphi_r(x, y)]$$  \hspace{1cm} (3)

respectively, where $o(x, y)$, $\varphi_o(x, y)$, $r(x, y)$ and $\varphi_r(x, y)$ are the amplitude and phase of the object and reference waves, respectively. The intensity of the hologram $I(x, y)$ recorded by the CMOS camera can be expressed as:

$$I(x, y) = |O(x, y) + R(x, y)|^2$$
$$= |O(x, y)|^2 + |R(x, y)|^2 + 2o(x, y)r(x, y) \cos[\varphi_o(x, y) - \varphi_r(x, y)]$$  \hspace{1cm} (4)

As in conventional double optical path interference, $I(x, y)$ can be represented as:

$$I(x, y) = a(x, y) + b(x, y) \cos[\varphi(x, y)]$$  \hspace{1cm} (5)

where $a(x, y)$ is the hologram background, $b(x, y)$ is the modulation, and $\varphi(x, y)$ is the phase difference between the two optically coherent beams. The phase $\varphi(x, y)$ in Equation (2) can be modified by adding the term $\Delta \varphi(x, y)$, which assumes values of 0, $\frac{\pi}{2}$, $\pi$ and $\frac{3\pi}{2}$. As such, the corresponding wavelengths become 632.85, 632.85219, 632.85438, and 632.8567 nm according to Formula (2). The inclusion of wavelength tuning then produces four-step phase-shifting holograms denoted by $I_1(x, y)$, $I_2(x, y)$, $I_3(x, y)$ and $I_4(x, y)$. Based on reference [31], the required phase difference can be calculated as:

$$\varphi(x, y) = \arctan \frac{I_4(x, y) - I_2(x, y)}{I_1(x, y) - I_3(x, y)}$$  \hspace{1cm} (6)
A basal plate was also included to accurately retrieve the object wave front and reconstruct basal holograms. The corresponding phase difference \( \varphi_b(x, y) \) can be expressed as:

\[
\varphi_b(x, y) = \varphi_{ob}(x, y) - \varphi_{rb}(x, y)
\] (7)

where \( \varphi_{ob}(x, y) \) and \( \varphi_{rb}(x, y) \) are the phases of the object beam and reference beam, respectively.

A functional micro-optics sample was placed on the basal plate for testing. In this configuration, the phase difference \( \varphi_m(x, y) \) between the two beams could be expressed as:

\[
\varphi_m(x, y) = \varphi_{ob}(x, y) + \varphi_{om}(x, y) - \varphi_{rb}(x, y)
\] (8)

where the phase \( \varphi_{om}(x, y) \) introduced in the test component can be calculated using:

\[
\varphi_{om}(x, y) = \varphi_m(x, y) - \varphi_b(x, y)
\] (9)

3. Results and Discussion

The viability of the proposed reconstruction technique for wavelength-tuning common-path DHM was assessed experimentally. A micro-lens array was used as a functional micro-optics sample to establish a consistent experimental procedure. The details of this process follow.

A glass basal plate was placed on the specimen stage in the imaging plane of the micro-objective. Phase-shifting holograms were then recorded by a CMOS camera as the laser wavelength was tuned according to Formula (2). Figure 4a shows an example of a recorded hologram, in which the holographic interferometry fringe is evident in the magnified portion of the image. Basal phase differences, and the corresponding wrapped and unwrapped phases, were then calculated using Equation (6), as shown in Figure 4b,c.

![Figure 4. Reconstructed phase data for the basal plate, including (a) the hologram, (b) the wrapped phase map, and (c) the unwrapped phase map.](image-url)
A micro-lens array with a lens diameter of 150 µm, a designed sag height of 2.6 µm, and a refractive index of 1.515 was placed on the basal plate. Its position was adjusted to match the imaging plane of the micro-objective. The holograms were collected after laser tuning, with phase differences modulated by the micro-lens array (see Figure 5a). The wrapped and unwrapped phases could then be determined, as shown in Figure 5b,c.

![Figure 4. Reconstructed phase data for the basal plate, including (a) the hologram, (b) the wrapped phase map, and (c) the unwrapped phase map.](image)

![Figure 5. Reconstructed phase data for the micro-lens array, including (a) the hologram, (b) the wrapped phase map, and (c) the unwrapped phase map.](image)

According to the Equation (9), the phase difference modulated by the micro-lens array was determined using a subtraction algorithm. Figure 6 shows the results of subtracting Figure 4c from Figure 5c. In the proposed technique, phase-shifting holograms can be acquired without any mechanical movement. In addition, the magnified portion of the hologram shown in Figure 4a clearly exhibits an interferometry fringe. As such, a phase-shifting algorithm (as opposed to a fast Fourier transform as shown in Figure 6c,d) was adopted to reconstruct the phase, to prevent the elimination of high-frequency information. It is evident that the reconstructed phase results include more frequency components and a detailed structure.

The resulting phase measurements were verified using the 3D profile of a micro-lens in a cross-test experiment. Phase results were translated to the physical objective profile by considering the central wavelength of the tuning laser, the refractive index of the specimen, and the lateral device magnification. The systematic magnification was determined to be 9.5× based on calibration with a USAF 1951 resolution target. The 3D profile of the micro-lens array was acquired using a central wavelength of 632.85 nm and a refractive index of 1.515, as shown in Figure 7a. The section profile for the array was calculated along the dashed line of Figure 7a, as represented by the blue line in Figure 7b.
Figure 6. The results of phase measurements for the micro-lens array, including (a) the 2D map and (b) the 3D distribution reconstructed by phase shifting, (c) the 2D map, and (d) the 3D distribution reconstructed by fast Fourier transform.

Figure 7. Measurement results for the micro-lens array, including (a) the 2D map, (b) a profile map along the dashed line shown in (a), and (c) the residual error.
A cross test was implemented to verify the correctness of the proposed DHM technique, using a ZYGO NEWVIEW 8200 3D optical surface profiler with a 10× Mirau interferometry objective. The raw data were recorded as DAT format files and uploaded to MATLAB. Section lines were then extracted as indicated by the red line in Figure 7b. It is evident from the figure that these two measurements of the micro-lens array profile are in excellent agreement. Some residual error was observed (a PV value of 0.7 μm, RMS value of 0.16 μm), as shown in Figure 7c. These errors were larger at the extremum of the section profile, as the two measurements were not perfectly aligned in space position, and other influencing factors were not considered in the new configuration. This will be the focus of further research.

4. Conclusions

This study presented a wavelength-tuning common-path DHM technique for quantitative phase imaging of functional micro-optics components. The methodology included a pinhole diffraction-based reference wave front and a wavelength-tuning phase-shifting glass plate. The configuration allows the transmission phase of functional micro-optics components to be precisely quantified and systematic error to be suppressed. This enables wavelength-tuning-based common-path DHM for accurate transmission phase measurements of functional micro-optics components.

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