Optics Communications 359 (2016) 272–278

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

High speed moire based phase retrieval method for quantitative phase imaging of thin objects without phase unwrapping or aberration compensation

Shouyu Wang [a,*], Keding Yan [b], Liang Xue [c]

[a] Department of Optoelectronic Information Science and Engineering, School of Science, Jiangnan University, Wuxi, Jiangsu 214122, China
[b] School of Electronic Information Engineering, Xi'an Technological University, Xi'an 710032, China
[c] College of Electronics and Information Engineering, Shanghai University of Electric Power, Shanghai 200090, China

ARTICLE INFO

Article history:
Received 2 July 2015
Received in revised form
19 September 2015
Accepted 29 September 2015

Keywords:
Phase retrieval
Quantitative interferometric microscopy
Phase distribution measurements

ABSTRACT

Phase retrieval composed of phase extracting and unwrapping is of great significance in different occasions, such as fringe projection based profilometry, quantitative interferometric microscopy and moire detections. Compared to phase extracting, phase unwrapping occupies most time consuming in phase retrieval, and it becomes an obstacle to realize real time measurements. In order to increase the calculation efficiency of phase retrieval as well as simplify its procedures, here, a high speed moire based phase retrieval method is proposed which is capable of calculating quantitative phase distributions without phase unwrapping or aberration compensation. We demonstrate the capability of the presented phase retrieval method by both theoretical analysis and experiments. It is believed that the proposed method will be useful in real time phase observations and measurements.

1. Introduction

Fringe measurements including fringe projection based profilometry, quantitative interferometric microscopy and moire detections, achieve much attention because they can provide quantitative phase information of samples which are helpful to determine the profiles of the surfaces, measure the shapes of the lens, and obtain the structures of different cells [1]. To obtain the phase information from fringe patterns, phase retrieval, often composed of phase extracting and unwrapping, is needed to transform the fringe intensity into continuous phase distribution.

Phase extracting is applied to calculate the phase distributions from fringes, and different algorithms are proposed: phase shifting approaches such as four step method and principal component analysis method [2,3] are designed only for static measurements since they need more than one interferogram for phase recovery. These approaches often own high accuracy, but they are limited by their low time resolution. To satisfy the requirements of dynamic measurements, single shot based phase extracting methods according to off-axis interference are employed as Fourier transform based approach [4,5] and Hilbert transform based approach [6–10]. Since quantitative phase distribution can be obtained from single interferogram, these off-axis interference based extracting methods are widely used in live cell phase imaging combining with real time quantitative interferometric microscopy [11–15].

Because arc tangent computing is used in phase extracting, the extracted phase is wrapped in the range of $[-\pi, \pi]$, phase unwrapping is needed to obtain the continuous phase by discontinuity recognition and elimination. However, compared to phase extracting, phase unwrapping occupies most time in phase retrieval which becomes an obstacle of realizing phase measurements in real time [16,17]. High speed phase unwrapping algorithm is proposed as pixel shifting phase unwrapping algorithm, but it is easily influenced by noise [18]. Dual-wavelength method is another idea for fast phase unwrapping [19], however, all phase discontinuities cannot be eliminated when the field of view is larger than the least common multiple of dual wavelengths. Additionally, phase unwrapping free approach is presented according to background removal [20], unfortunately, it is unable to recover the accurate phase if the sample is located at phase discontinuities. Moreover, because of aberrations in the optical systems, after phase unwrapping, phase compensation is needed for background aberration elimination. Various phase compensation methods are proposed as extrapolation method, background aided method, self-referencing method and background fitting method, etc. [21–26]. The added phase compensation procedure increases

* Corresponding author.
E-mail addresses: wsy_photonics@yahoo.com (S. Wang), xueliangokay@gmail.com (L. Xue).

http://dx.doi.org/10.1016/j.optcom.2015.09.100
0030-4018/

the complexity of phase retrieval and the processing time consuming as well.

Here, in order to increase the calculation efficiency of phase retrieval, a high speed moire based phase retrieval method for thin object phase imaging is presented, which is able to recover quantitative phase distribution automatically without phase unwrapping or compensation. Using this method, an interferogram of sample, together with a background interferogram, is needed for phase retrieval. The capability of the presented method is demonstrated by both theoretical analysis and experiments. We believe the proposed method is of great potential in wide applications such as fringe projection based profilometry and quantitative interferometric microscopy.

2. Method

In this section, the principle of high speed moire based phase retrieval method is explained according to quantitative interferometric microscopy. An interferogram captured by quantitative interferometric microscopy can be explained by Eq. (1).

$$I(x, y) = a(x, y) + b(x, y)\cos[\Phi(x, y)] \tag{1}$$

In Eq. (1), $a(x,y)$ is the DC term and $b(x,y)$ is the modulation term. As the illumination intensity is equally distributed in the field of view, additionally, cells under visible light illumination are almost transparent, $a(x,y)$ and $b(x,y)$ can be both treated as uniform distributions. Moreover, since there is often more than one fringe in the interferograms, the values of a and b can be easily evaluated. $\Phi(x,y)$ is the phase distribution including sample, background and aberrations. Eq. (2) illustrates the simplified equation of interferogram, assuming the illumination is uniform and the sample absorption is rather low, thus it can be ignored.

$$I = a + b\cos\left[k_x x + k_y y + \varphi(x, y) + \varphi_a(x, y)\right] \tag{2}$$

In Eq. (2), $k_x x$ and $k_y y$ indicate background wavefront tilt in two orthogonal directions induced by off-axis interference, φ is sample phase distribution and φ_a is the phase distribution induced by aberrations in the imaging system. As illustrated before, the proposed method requires another interferogram, which loses the sample phase as shown in Eq. (3).

$$I_0 = a + b\cos\left[k_x x + k_y y + \varphi_a(x, y)\right] \tag{3}$$

As a and b in Eqs. (2) and (3) can be easily evaluated, DC terms can be removed from these two interferograms.

$$I' = b\cos\left[k_x x + k_y y + \varphi(x, y) + \varphi_a\right] \tag{4}$$

$$I_0' = b\cos\left[k_x x + k_y y + \varphi_a\right] \tag{5}$$

With Euler equation, these DC removal interferograms can be presented as Eqs. (6) and (7).

$$I' = \frac{b}{2}\exp\left(i\left(k_x x + k_y y + \varphi(x, y) + \varphi_a\right)\right) + \frac{b}{2}\exp\left(-i\left(k_x x + k_y y + \varphi(x, y) + \varphi_a\right)\right) \tag{6}$$

$$I_0' = \frac{b}{2}\exp\left(i\left(k_x x + k_y y + \varphi_a\right)\right) + \frac{b}{2}\exp\left(-i\left(k_x x + k_y y + \varphi_a\right)\right) \tag{7}$$

If we multiply Eqs. (6) and (7)

$$\tilde{I} = \frac{b^2}{4}\left\{\exp\left[i\left(2k_x x + 2k_y y + \varphi(x, y) + 2\varphi_a\right)\right] + \exp[i\varphi(x, y)] + \exp\left[-i\left(2k_x x + 2k_y y + \varphi(x, y) + 2\varphi_a\right)\right] + \exp[-i\varphi(x, y)]\right\} \tag{8}$$

It is seen from Eq. (8) that the multiplication result can be divided into two parts with different spatial frequencies. Compared to the high frequency components, low frequency components are more important since they only contain the phase information of the samples, besides, both aberrations and background are eliminated. With a low pass filter, low frequency components can be obtained as Eq. (9).

$$\hat{I} = \frac{b^2}{4}\{\exp[i\varphi(x, y)] + \exp[-i\varphi(x, y)]\} = \frac{b^2}{2}\cos[\varphi(x, y)] \tag{9}$$

The principle of this method is similar to moire technique which focuses on the information with frequency difference. With low frequency filter on the multiplication of interferograms, only the sample phase information is reserved, while high frequency components including aberrations and background are all removed. Finally, with normalization and arc cosine computing, the phase distribution can be retrieved. Compared with traditional arc tangent computing, the range of arc cosine computing is much less which is only $[0, \pi]$, therefore, the proposed method is only able to recover the phase of thin objects, while it is worth noting the phase distributions of many biological cells are less than π, the proposed method still can be applied in quantitative phase microscopy for observing these biological cells. Additionally, since the relatively large phase distributions of aberrations and background are eliminated, and the phase distributions of biological cells are often small, the continuous phase can be obtained without phase wrapping or aberration compensation.

3. Simulation

As illustrated in Section 2, the operation steps of the proposed method is shown in Fig. 1. After obtaining the multiplication of the interferograms with and without samples, the low frequency pass filter is then applied on interferogram multiplication for low frequency component extraction, and finally the quantitative phase distribution can be retrieved according to arc cosine computing. Here, Butterworth low pass filter is used in low frequency information extraction for ringing effect inhibition.

Because the proposed method is only able to retrieve phase of thin objects, in the simulation, the red blood cell (RBC) model [27] is used since its maximum phase is less than π. The RBC model obtained from statistical observations is explained by Eq. (10).

$$z(\rho) = \sqrt{1 - \left(\frac{\rho}{a}\right)^2}\left[0.72 + 4.152\left(\frac{\rho}{a}\right)^2 - 3.426\left(\frac{\rho}{a}\right)^4\right] \tag{10}$$

Eq. (10) analytically depicts a RBC model on the ρ–z plane in a cylindrical coordinate system. The biconcave cell has a diameter of $2a = 7.65$ μm, and maximum and minimum thickness of 2.84 and 1.44 μm, respectively. In experiments, since the RBCs were cultured in 0.9% mass fraction NaCl solution, the measured phase distribution is actually the integral of the refractive index difference Δn between the cell (~1.40) and surrounding solution (~1.34) along the cell thickness as shown in Eq. (11).

$$\Delta\varphi = \frac{2\pi}{\lambda}\int \Delta n \cdot dz \tag{11}$$

Since the RBC is a cell with homogeneous refractive index, Eq. (11) can be simplified as Eq. (12):