Optics Communications 383 (2017) 537–544

Contents lists available at ScienceDirect

Optics Communications

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

Quantitative interferometric microscopy with two dimensional Hilbert transform based phase retrieval method

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ARTICLE INFO

Keywords:
Quantitative interferometric microscopy
Two dimensional Hilbert transform
Phase retrieval

ABSTRACT

In order to obtain high contrast images and detailed descriptions of label free samples, quantitative interferometric microscopy combining with phase retrieval is designed to obtain sample phase distributions from fringes. As accuracy and efficiency of recovered phases are affected by phase retrieval methods, thus approaches owning higher precision and faster processing speed are still in demand. Here, two dimensional Hilbert transform based phase retrieval method is adopted in cellular phase imaging, it not only reserves more sample specifics compared to classical fast Fourier transform based method, but also overcomes disadvantages of traditional algorithm according to Hilbert transform which is a one dimensional processing causing phase ambiguities. Both simulations and experiments are provided, proving the proposed phase retrieval approach can acquire quantitative sample phases with high accuracy and fast speed.

1. Introduction

As one of phase imaging techniques, quantitative interferometric microscopy (QIM) can acquire sample phases from single-shot interferograms [1–13], thus compared to methods based on transport of intensity equation [14–18] and ptychography [19–21], it is well suited for real time cellular observations and measurements. In QIM, phase retrieval algorithms are adopted to extract phases from fringes. Among them, fast Fourier transform (FFT) based approaches are available because of their good noise suppression capability [22–24]. However, high frequency components are lost indicating sample details are missing which decreases phase retrieval accuracy obviously. In order to compromise information between noise suppression and detail preservation, Hilbert transform (HT) based algorithms [25–30] which can extract more sample information from interferograms are presented. Considering their advantages in high-accurate phase retrieval, they have been used in various fields especially in low noise cases. While in QIM, closed circular fringes often appear in interferograms influenced by wavefront distortions caused by imaging system aberrations, however, these methods can only do well in open fringe occasion, while for closed patterns, phase ambiguities occur causing errors directly affecting the quality of phase unwrapping. Though phase ambiguities can be compensated in phase retrieval with additional procedures, such as Li et al. designed four phases stitching algorithm to recombine recovered phases [31]; Ge et al. transformed circular fringes into open fringes via coordinate transformation thus FFT method can be used directly [32]; Wang et al. proposed radial HT based phase retrieval to extract phases according to polar coordinates [33]. However, additional coordinate transformation and phase recombination lead to complicated operations and calculating errors. Besides, these time consuming procedures limit their potential applications in real time quantitative phase imaging. Thus direct phase retrieval dealing with closed fringes with high accuracy and fast speed in QIM is still in demand.

Here, in order to avoid phase ambiguities in traditional phase retrieval methods, while to retain advantages as detail preservation and fast computation as well, a two dimensional HT (2DHT) [34,35] based phase retrieval method is adopted in QIM. Both numerical simulations and experimental measurements are provided, proving QIM based on the proposed phase retrieval approach can realize cellular phase imaging with high accuracy and fast speed.

2. Numerical simulations and analysis

Firstly, theoretical derivation is presented: fringe patterns captured by QIM can be explained as Eq. (1).

$$I(x, y) = a(x, y) + b(x, y)\cos(\theta(x, y) + \varphi(x, y)) \tag{1}$$

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http://dx.doi.org/10.1016/j.optcom.2016.10.008
Received 26 August 2016; Received in revised form 29 September 2016; Accepted 1 October 2016
Available online 11 October 2016
0030-4018/

I(x,y) represents the intensity of interferogram, a(x,y) and b(x,y) are treated as constants with uniform distributed illumination and weak scattering samples in measurements, θ(x,y) indicates wavefronts induced by both phase distortions and tilting off-axis interference, and φ(x,y) is the sample phase. Similar to traditional HT methods, offset should be firstly removed as Eq. (2).

$$I_c(x, y) = b(x, y)\cos(\theta(x, y) + \varphi(x, y)) \tag{2}$$

In order to extract phases from fringes, orthogonal component of offset removal interferogram, which is phase shifting fringe pattern, is needed. For complicated interferograms with closed curved fringes, 2DHT is adopted as explained in Eq. (3), in which HT2 indicates 2DHT operator, FFT and IFFT are Fourier transform and inverse Fourier transform, respectively. ψ(x,y) is spiral phase ranging from 0 to 2π.

$$HT2(*) = IFFT(\exp(i\psi(x, y))FFT(*)) \tag{3}$$

With 2DHT operator functioned on I_c, its orthogonal component I_s can be computed by Eq. (4).

$$HT2(I_c) = i\exp(i\eta(x, y))b(x, y)\sin(\theta(x, y) + \varphi(x, y)) = i\exp(i\eta(x, y))I_s \tag{4}$$

However, I_s cannot be obtained directly since fringe direction η(x,y) is coupled. In order to compute fringe direction rapidly, fringe gradient combining with high speed unwrapping is designed. Firstly, gradient in both x and y axes are calculated thus fringe direction can be acquired, while because of arc-tangent computation ranging in (-π/2, π/2), there is wrapping in obtained fringe angles. Next, in order to achieve continuous fringe directions, wrapping locations should be recognized according to multiplication of fringe angle and its pixel shifting distribution. It is because only at wrapping locations, the multiplication results are relatively large negative values close to $-\pi^2/4$ due to a relatively large negative phase value (~−π/2) and a relatively large positive phase value (~+π/2) at the phase discontinuity. Finally, by tracking these minimum values, a π phase step is generated to compensate the wrapped angle [36], thus continuous fringe direction distribution can be acquired. The detail procedure is shown in Fig. 1..

Noting that there is no iteration and determination procedure in additional automatic fringe direction computation, thus it can ensure the rapid processing speed in phase retrieval. Then, wrapped phases are extracted after η(x,y) calculation.

$$\theta(x, y) + \varphi(x, y) = \arctan\left(\frac{-i\exp(-i\eta(x, y))HT2(I_c)}{I_c}\right) = \arctan\frac{I_c}{I_s} \tag{5}$$

With proposed 2DHT algorithm, no ambiguity occurs in extracted phases, but phase unwrapping is still needed to expand the wrapped distribution into continuous one. Since θ(x,y) is unwanted distortion in QIM, φ(x,y) can only be recovered after θ(x,y) is removal using phase compensation [37,38]. The whole process of 2DHT in phase retrieval is listed as Fig. 2 in details..

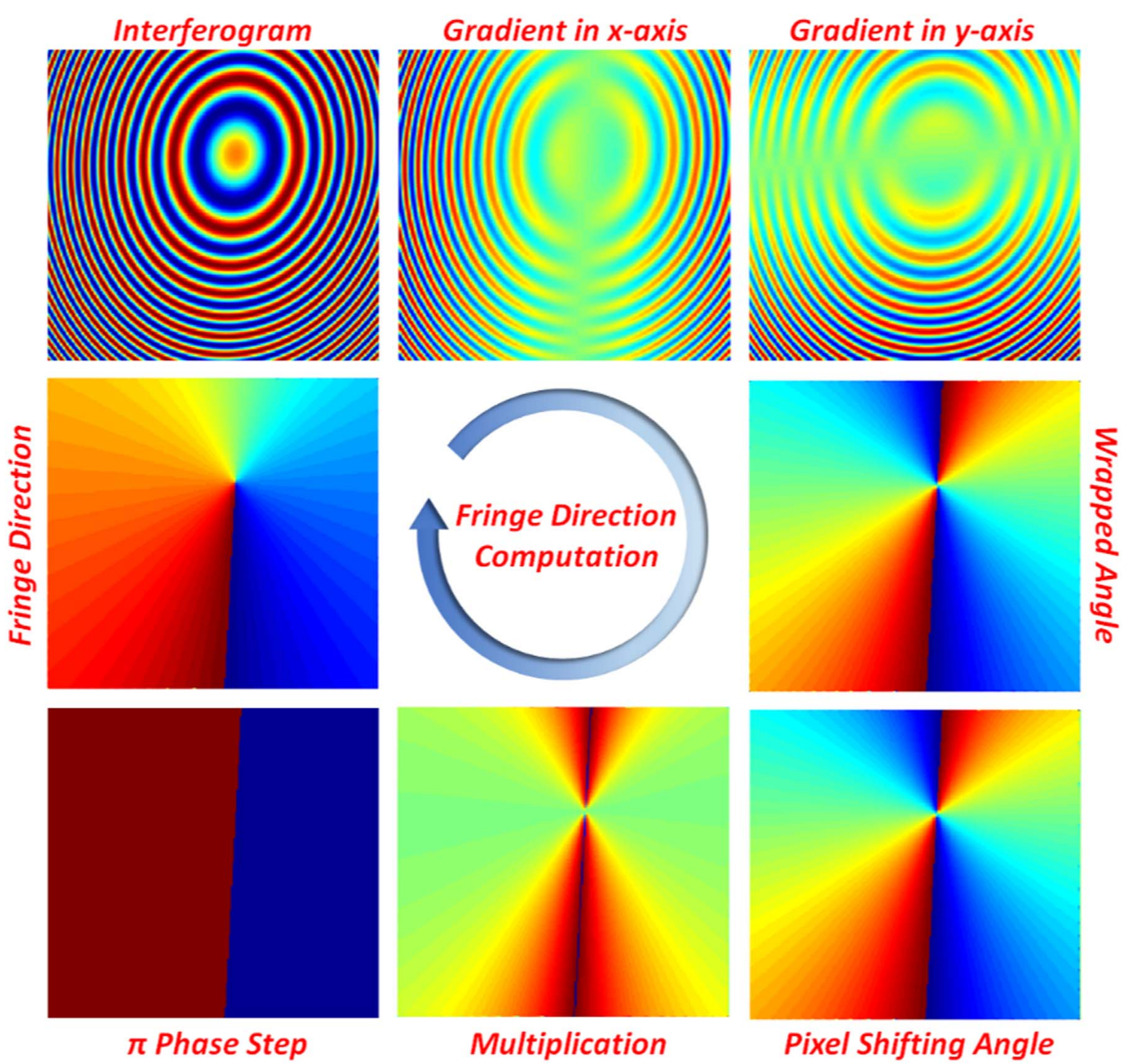

Fig. 1. Process of fringe direction computation.