ARTICLE IN PRESS

Current Applied Physics xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Current Applied Physics

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

Rough surface characterization using off-axis digital holographic microscopy compensated with self-hologram rotation

Dahi Ghareab Abdelsalam Ibrahim

Engineering and Surface Metrology Lab., National Institute of Standards, Tersa St., El haram, El Giza, Egypt

ARTICLE INFO

Keywords:
Digital holographic microscopy
Optical metrology
Rough surface characterization
Phase unwrapping

ABSTRACT

In this paper, an off-axis digital holographic microscopy compensated with self-hologram rotation is presented. The process is implemented via subtracting the unwrapped phase maps of the off-axis parabolic hologram and its rotation 180° to eliminate the tilt induced by the angle between the spherical object wave *O* and the plane reference wave *R*. Merit of the proposed method is that it can be done without prior knowledge of physical parameters and hence can reconstruct a parabolic hologram of 1024 × 768 pixels within tens of milliseconds since it doesn't require a digital reference wave. The method is applied to characterize rough gold bumps and the obtained results were compared with those extracted from the conventional reconstruction method. The comparison showed that the proposed method can characterize rough surfaces with excellent contrast and in real-time. Merit of the proposed method is that it can be used for monitoring smaller biological cells and micro-fluidic devices.

1. Introduction

Digital holographic microscopy (DHM) is a robust, precise measuring technique widely used in surface metrology without contacting the sample being tested [1–3]. Testing surfaces with tiny irregularities inevitably require a microscope objective (MO) with high magnification to magnify the detail of such tiny irregularities [4]. Conventionally, to retrieve the object wave (amplitude and phase) of the parabolic fringes which contoured such tiny irregularities, a simulated conjugate digital lens is used to eliminate the tilt induced by the off-axis angle between the spherical object wave (*O*) and the plane reference wave (*R*) [4]. The main drawback of this method is that it takes a long time to adjust the parameters that simulate the conjugate digital lens. Alternatively, an identical MO positioned in the reference arm of the interferometer is used to mitigate or compensate the off-axis tilt between *O* and *R*. The main drawback of this method in terms of cost and careful adjustment is the requirement of two identical microscope objectives to eliminate the off-axis tilt. By and large, such traditional reconstruction methods with all drawbacks are adequate for featuring smooth surfaces. To our knowledge, no comparable efforts were given to reconstruct rough surfaces due to speckle noise which debases the image quality seriously [5]. It is worth mentioning that suppression of speckle noise in the reconstructed object wave is considered a difficult problem because of its badly statistical regularity since such speckle noise appears as a kind of multiplicative noise as stated in Ref. [5]. Some circumvents such as using low coherent light instead of laser illumination have been put forward to supress the speckle noise, but this circumvent debases the quality of the reconstructed image [6]. Another circumvent is done by using median filtering, Wiener filtering, mean filtering [7,8], nonlocal means filtering [9], wavelet filtering [10], and windowed Fourier filtering [11]. However, the treatment of this circumvent is not ideal due to loss of intensity. In this paper, we applied the proposed reconstruction method which is compensated with self-hologram rotation to characterize rough surface with excellent results. As far as we know, this is the first time that a parabolic hologram compensated with self-hologram rotation is employed to characterize a rough surface with excellent contrast. It is worth mentioning that Deng et al. [12], applied this idea for off-axis open fringes, however, no comparable efforts were given to compensate the parabolic hologram by self-hologram rotation. The idea as explained in Ref. [12] is used to eliminate the tilt due to off-axis geometry in the off-axis hologram. Here, we modified the approach in Ref. [12] to compensate the tilt due to off-axis geometry in the parabolic holograms. The parabolic hologram is produced when plane waves from the reference interfere with spherical waves from the object. By rotating the parabolic hologram (I_{par}) 180° clockwise or counter clockwise, a rotated hologram (I_{rot}) is then obtained automatically. By subtracting the retrieved unwrapped phase φ_{rot} of the rotated hologram from the retrieved unwrapped phase φ_{par} of the parabolic hologram, the tilt between the spherical object *O* and the plane reference wave *R* is completely removed without adjusting any parameters. We claim that

E-mail address: dahi.abdelsalam@nis.sci.eg.

https://doi.org/10.1016/j.cap.2018.07.003
Received 19 May 2018; Received in revised form 27 June 2018; Accepted 5 July 2018

the subtraction of unwrapped phase from the parabolic hologram and the unwrapped phase from its rotation in addition to using an intermediate coherent light (SLD) cancels out the speckle noise of the rough surface. Here, the MO used must be free from optical aberrations, otherwise the reconstructed object wave is contaminated with optical aberrations such as wave front curvature [13], spherical aberration [14], chromatic aberration [15], and astigmatism [16]. Such optical aberrations in the object wave can be compensated by numerical fitting techniques such as Zernike polynomials [17]. In this paper, we applied this method to characterize Au rough bumps in real-time and compare the results with conventional reconstruction method (simulated conjugate digital lens). The comparison showed that the rough bumps appear clearly in the reconstructed phase-contrast image of the proposed method. We claim that the clearness of the rough bumps in phase contrast-image is due to two things: the first is due to using an intermediate coherent light and the second is due to the proposed reconstruction method which depends on its compensation on self-hologram rotation, not on the simulated conjugate digital lens as in conventional reconstruction method. Merit of the proposed method is that it can be applied without prior knowledge of physical parameters such as wave vector components, focal lengths, and positions of the optical components, and hence can reconstruct a parabolic hologram of 1024 × 768 pixels within tens of msec. Another merit is that it doesn't need a digital reference wave, which is always used in the conventional reconstruction methods. Moreover, it is enabling to assign the edges of the rough object (bump) clearly, whereas the white light interference (WLI) microscope fails to assign.

2. The sample being tested

Photograph of the Au bumps being tested is shown in Fig. 1(a).

It is worth mentioning that characterization of rough surfaces by digital holographic microscopy is considered a difficult problem which has not been solved yet. Also, characterization of such gold bumps precisely is essential in industry because of its diverse applications in surface acoustic wave filters used in smartphones and other RF applications [18–22]. The rough bumps of Fig. 1(a) have been investigated by WLI and the three-dimensional (3D) phase image is shown in Fig. 1(b). As seen in Fig. 1(b), the WLI fails to characterize the Au rough surfaces of the bumps with excellent contrast, since the edges of each bump can't be determined precisely (see the green color in Fig. 1(b) which describes the borders of each bump). Fig. 1(c) shows a detail of ten Au bumps in the black rectangle of Fig. 1(a) captured by high

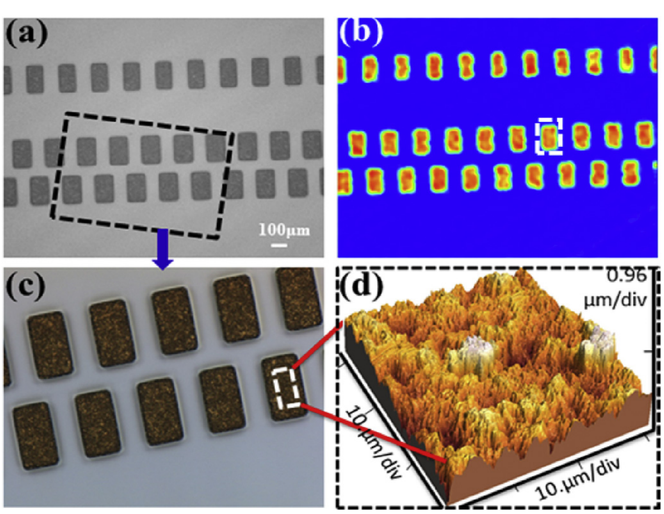

Fig. 1. (a) Photograph of the Au rough pumps. (b) Visualization of (a) with WLI. (c) Imaging of the black rectangle of (a) with high magnification. (d) Investigation of the white rectangle of (c) with AFM.

magnification microscope. One bump in the white rectangle of Fig. 1(c) has been featured by an atomic force microscope (AFM) to see how rough the bump surface is. A projected area of size 900.0 µm^2 (30 µm × 30 µm) from the area of the white rectangle of Fig. 1(c) featured by the AFM is shown in Fig. 1(d). Data retrieved by the AFM are as follows; rms rough (Rq) is 261.7 nm, average roughness (Ra) is 204.6 nm, and roughness of peak to valley Rp-v is 1.925 µm. It is worth mentioning that very rough surfaces in which the roughness exceeds the wavelength [23], a high coherent light is not able to characterize the topography well due to speckle noise. Using an extended low-coherent light for rough surface measurement [24–28] may debase the quality of the reconstructed image. In this paper, we overcome these problems by using an intermediate coherent light (SLD) to characterize the rough surfaces of the Au bumps. We claim that using such intermediate coherent light reduces the speckle noise to some amount and the remainder of the speckle noise is reduced by the proposed reconstruction method which is compensated by self-hologram rotation. Due to the failure of WLI microscope to assign the borders of the rough bumps clearly and the problem of time consuming to test a small area in one bump by AFM, we claim that the proposed method has solved the bump borders assignment whereas the WLI microscope fails and the speed whereas the AFM fails. Here, the surfaces of the Au bumps are assumed identical with area of bump size of 100 µm (width) x 200 µm (length).

3. Experimental setup

A schematic diagram of the Twyman-Green interferometer used for rough surface characterization is depicted in Fig. 2. A microscope objective (MO) of 10× in the test arm is used to magnify the details of the sample. Light from SLD with coherence length of around 20 µm controlled spatially by slits is used to illuminate the interferometer.

The hologram intensity of one pixel against the displacement of the reference arm of the interferometer at varied slit widths (inlet width = exit width) ranged from 20 µm to 200 µm is shown in Fig. 3(a). The coherence length at each varied slit width is then calculated as shown in Fig. 3(b). As seen in Fig. 3(b), the coherence length is estimated to be 20 µm at slit width of 150 µm. The controlled light at equal widths of both inlet and exit slits at 150 µm is expanded by the MO1 and the collimating lens as shown in Fig. 2. A plane wave front leaves the collimating lens and the non-polarized beam-splitter (NPBS) divides the wave front into two copies: a transmitted and a reflected portion. The light transmitting the NPBS enters the reference arm of the interferometer, while the light reflecting the NPBS enters the test arm of the interferometer via a normal microscope objective lens MO2 (10×, NA = 0.30) to magnify the details of the rough Au bumps patterned on the sample surface. The reflected spherical light from the sample interferes with the plane light reflected from the reference mirror after passing the NPBS while returning. The wavelength of the SLD light source used is 683.5 nm and a CCD sensor with 1024 × 768 pixels with pixel size of 4.65 µm used to record the parabolic hologram via an imaging lens (3×, NA = 0.1) as shown in Fig. 2. Once the parabolic hologram obtained, it is processed directly into a written program with MATLAB to extract amplitude and phase of the object separately. To see the performance of the proposed method in comparison with the conventional reconstruction method, we investigated the same object with high coherent light with the same optical setup of Fig. 2 and the obtained parabolic hologram was reconstructed conventionally as explained in detail in sec.4.

4. Conventional reconstruction method

Here, we used a long coherent light of laser diode of wavelength λ = 635 nm instead of SLD light in the schematic diagram of Fig. 1 and used a conventional reconstruction method termed a simulated conjugate digital lens (explained by the author in Ref. [8]) to eliminate the tilt induced by the off-axis angle between the spherical object wave (O)