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Dimensional metrology of smooth micro structures utilizing the spatial modulation of white-light interference fringes

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ABSTRACT

Dimensional metrology for micro structure plays an important role in addressing quality issues and observing the performance of micro-fabricated products. In white light interferometry, the proposed method is expected to measure three-dimensional topography through modulation depth in spatial frequency domain. A normalized modulation depth is first obtained in the xy plane (image plane) for each CCD image individually. After that, the modulation depth of each pixel is analyzed along the scanning direction (z-axis) to reshape the topography of micro samples. Owing to the characteristics of modulation depth in broadband light interferometry, the method could effectively suppress the negative influences caused by light fluctuations and external irradiance disturbance. Both theory and experiments are elaborated in detail to verify that the modulation depth-based method can greatly level up the stability and sensitivity with satisfied precision in the measurement system. This technique can achieve an improved robustness in a complex measurement environment with the potential to be applied in online topography measurement such as chemistry and medical domains.

1. Introduction

Micro devices play a key role in many domains including integrated circuits (IC), medical cure, and chemistry applications [1–5]. Three-dimensional measurement of micro structure is an area with growing needs and interest since it can always have a significant influence on the performance of micro products. In the past few years, various methods have been proposed to obtain the surface topography such as atomic force microscopy (AFM), scanning tunnel microscopy (STM), stage profiler and confocal scanning microscopy [6–9]. Some of them could achieve a high precision while it may destroy the measured structure because of the contacting methods. During the past two decades, white-light interferometry (WLI) has been widely applied for precise profile metrology of engineering surface especially micro structures due to its large measurement range, noncontact and high precision [10–17].

Previously, various techniques and algorithms have been proposed in white-light interferometry, where signal processing is typically based on envelope and phase evaluation [18–22]. Chen, S and Palmer, AW proposed a special digital signal processing technique based on a centroid algorithm to complete fringe order identification in white light interferometry, where the intensity values of each pixel along scanning direction were calculated [23]. Sandoz, P and Devillers, R put forward a white-light phase-shifting method for interferometry, in which the absolute phase would be measured according to several recorded intensities [24]. Harasaki, A described an improved vertical-scanning interferometry method to measure the topography without fringe-order ambiguity [25]. Kino, Gs stated a Hibert algorithm to obtain the envelope of the intensity correlogram to trace the zero optical difference in Mirau correlation microscope [26]. Nonetheless, most of the mentioned methods are likely to be negatively influenced by light fluctuations, external irradiance disturbance and temporally changeable reflectivity of the measured object.

In order to eliminate the harmful influences of the unpredictable fluctuations of light irradiance, this paper proposes a spatial modulation depth-based method to reshape the 3D topography of micro structures. A normalized modulation depth is first obtained in the image plane for each CCD image of an interference pattern individually. After that, the modulation depth of each pixel is analyzed along the scanning direction (z-axis) to obtain the corresponding height and finally reshape the topography of micro structure. The proposed technique would benefit from the characteristic of intensity modulation, where the zero-optical-difference point can be precisely located through suppressing the irradiance fluctuations. The final goal of this technique is to obtain the zero optical difference of each pixel, the corresponding scanning posi-

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tion and the topography data through tracing the largest-value point of the normalized modulation correlogram.

In the research, we will introduce the principle of the spatial modulation method, which contains light field distribution of broadband light interferometry, extraction of modulation depth and topography recovery algorithm. To verify the performance of the proposed method, a micro-dome sample has been measured. Results show that the proposed method based on spatial modulation analysis can greatly improve the measurement robustness through removing the negative influences of light instability, external disturbance and temporally changeable reflectivity of the measured object. Additionally, it will be more sensitive to locate the maximum point of modulation coherence curve which has only one peak while intensity coherence curve has too many fuzzy peaks. Benefiting from these superior performances, spatial modulation method is possibly promising to be applied in online topography measurement such as chemistry and medical domains.

2. Method

2.1. Zero optical difference location through spatial modulation

Fig. 1 shows a Mirau interferometer-based system of WLI for topography measurement of a micro structure [20,27,28]. In the proposed system, the light transmits through the interferometry objective (Mirau interferometer) which contains a beam splitter and a reference mirror whose diameter is several millimeters, where the light is divided into two lights by the beam splitter. One is focused on the measured sample and the other is on the reference spot mirror. The interferograms can be detected by a CCD camera. This is achieved through vertically scanning the sample using Piezo-electric Transducer (PZT) stage, where the interferograms can be simultaneously captured at each scanning position.

In white light interferometry, when intensities from the measurement arm and the reference arm are the same, the interference intensity field can be derived as

$$I(z) = I_0\left\{1 + \exp\left[-\left(\frac{z - h(x,y) - z_0}{l_c}\right)^2\right]\cos\left(4\pi\frac{z - h(x,y) - z_0}{\lambda_0}\right)\right\} \quad (1)$$

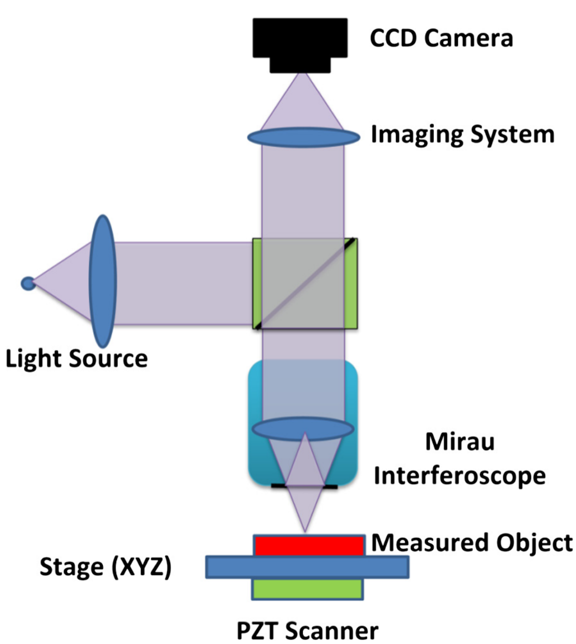

Fig. 1. Schematic of Mirau-based WLI system.

where I_0 is the background intensity, z illustrates the scanning distance, $h(x,y)$ describes the surface topography of the measured sample, z_0 presents the length of reference arm, λ_0 is the central wavelength, and l_c denotes the coherence length of the light source [29].

Although the illumination uniformity can be reliable due to the satisfying optical system design, the interference intensity can also be influenced by time instability of light source and external light disturbance. Consequently, the interference intensity distribution can be actually expressed as

$$I(x,y,z) = A(x,y,z) + B(z)\exp\left[-\left(\frac{z - h(x,y) - z_0}{l_c}\right)^2\right]\cos\left(4\pi\frac{z - h(x,y) - z_0}{\lambda_0}\right) \quad (2)$$

where $A(x,y,z)$ presents the changeable background intensity, $B(z)$ is the unstable intensity contrast along different scanning positions.

In the proposed method, in order to eliminate the negative influence caused by instable background intensity, we need to effectively exclude the background intensity from the interference intensity distribution. To produce a carrier frequency (also known as the base frequency) which will provide the extraction of spatial modulation, the measured sample is slightly tilted to develop a small angle between the light axis and the sample surface. When the sample is slightly tilted, at each given scanning position, the interference intensity distribution can be written as

$$I_{z_1}(x,y) = A_{z_1}(x,y) + B_{z_1}\exp\left[-\left(\frac{z_1 - (h(x,y) - kx) - z_0}{l_c}\right)^2\right] \times \cos\left(4\pi\frac{z_1 - (h(x,y) - kx) - z_0}{\lambda_0}\right) \quad (3)$$

where $A_{z_1}(x,y)$ is the background intensity at the scanning position z_1, B_{z_1} denotes the intensity contrast which is constant in *x*, *y*, *kx* is the initiatively tilted slope along *x* axis while *k* is slope factor. The equation can be rewritten as

$$I_{z_1}(x,y) = A_{z_1}(x,y) + B_{z_1}\exp\left[-\left(\frac{kx - h(x,y) + z_1 - z_0}{l_c}\right)^2\right] \times \cos\left(4\pi\frac{kx}{\lambda_0} + 4\pi\frac{z_1 - z_0 - h(x,y)}{\lambda_0}\right) \quad (4)$$

One can see that there is an added carrier frequency $2\frac{k}{\lambda_0}$. To simplify the expression, the intensity distribution can be described as

$$I_{z_1}(x,y) = A_{z_1}(x,y) + B_{z_1}\exp\left[-\left(\frac{kx - h(x,y) + z_1 - z_0}{l_c}\right)^2\right] \times \cos(2\pi fx + \phi(x,y)) \quad (5)$$

where $\phi(x,y) = 4\pi\frac{z_1 - z_0 - h(x,y)}{\lambda_0}$, $f = 2\frac{k}{\lambda_0}$.

Fig. 2 shows the simulated interferograms when selecting function 'Peaks' as the measured sample in WLI system. One can see that it is difficult to pick out the modulation when the fringe patterns are disordered, as shown in Fig. 2(b). As described previously, when the sample is tilted to develop a small angle with the optical path, there will be a carrier frequency spectrum in the frequency domain. The fringe contrast will be well-organized after slightly tilting the sample, and it will be approachable to extract the spatial modulation in the interferogram patterns, as shown in Fig. 2(c).

2.2. Extraction of spatial modulation depth

The algorithms in both spatial and frequency domains will be conducted to extract the modulation depth of each pixel in a defi-