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Simultaneous profiling of optically smooth and rough surfaces using dual-wavelength interferometry

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ABSTRACT

Interferometers are widely used in industry for surface profiling of microsystems. It can be used to inspect both smooth (reflective) and rough (scattering) surfaces in wide range of sizes. If the object surface is smooth, the interference between reference and object beam results in visible fringes. If the object surface is optically rough, the interference between reference and object beam results in speckles. Typical microsystems such as MEMS consist of both smooth and rough surfaces on a single platform. Recovering the surface profile of such samples with single-wavelength is not straight forward. In this paper, we will discuss a dual-wavelength approach to measure surface profile of both smooth and rough surfaces simultaneously. Interference fringe pattern generated on a combined surface is acquired at two different wavelengths. The wrapped phases at each wavelength are calculated and subtracted to generate contour phase map. This subtraction reveals the contour fringes of rough and smooth surfaces simultaneously. The dual-wavelength contour measurement procedure and experimental results will be presented.

***Keyword*:** dual-wavelength, interferometry, fringe analysis, surface profiling, microsystems

1. INTRUDUCTION

Characterization of surface shape is an important parameter in quality evaluation and metrology applications related to functionality, reliability and integrity of the microsystems or components [1-3]. Also, 3D shape of the test object is essential for the complete deformation studies where a careful analysis of sensitive vector orientation across the field-of-view is necessary for reliable quantitative measurements. The measured surface shape can be used to determine the dimensional accuracy of the manufactured components. In addition, the 3D surface profiling has also found important applications in non-destructive testing (NDT), reverse engineering, quality control, robot vision and tribology [4-6]. For surface proofing of smooth surfaces conventional dual-wavelength interferometry and for surface profiling of rough surfaces dual-wavelength speckle pattern interferometry are widely used. Using two different wavelengths in out-of-plane interferometry can reveal the shape of an object under investigation.

In two-wavelength method, a careful choice of wavelengths is important. The selected wavelengths enable the system to make use of long range surface profile analysis at synthetic or effective wavelength [7-9]. For smooth surfaces one can directly observe the interference fringes related to the surface shape, so single wavelength would be sufficient to measure the shape. But, for rough surfaces no fringes are visible due to the random speckle noise. Therefore to reveal the surface shape of a rough surface, the background random speckle noise must be eliminated. One way to reveal the shape is using phases measured at different wavelengths. If the phase of the surface (smooth or rough) under test is evaluated at two wavelengths, λ_1 and λ_2, then the difference between the two phases corresponds to the wrapped phase map that could have been generated with a longer wavelength given by the relation, synthetic wavelength, $\Lambda=\lambda_1\lambda_2/|\lambda_1-\lambda_2|$ [10-13]. Using this phase subtraction method for surface profiling of rough surface, the random background speckle noise (random distribution of intensity) will be eliminated to yield contour phase fringes. Further, using the two-wavelength method, the discontinuity between smooth and rough surfaces can be resolved and can be quantified as well [11, 14].

Microsystems usually have several composite materials, static and movable components. They also have typical surfaces which show discontinuities, like steps or holes. If the step height is less than $\lambda/2$, it can be measured using single wavelength. An unambiguous measurement of large step heights is possible, if the synthetic wavelength is chosen larger

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than the largest surface step. Dual-wavelength can be implemented in two different methods. Method-1: simultaneous illumination [15-17] and Method-2: sequential illumination [18, 19]. In method-1, the test object is illuminated simultaneously with a pair of two continuous wavelength (CW) visible lasers individually tuned to the appropriate wavelength difference. In method-2, the test object is illuminated sequentially at different wavelengths and the phase measured at each wavelength is subtracted to yield effective wavelength phase map fringes that contain the information pertaining to surface shape of the test object. By combining the dual-wavelength speckle interferometry with the temporal phase shifting it is possible to obtain the dynamic range of the effective wavelength for 3D surface profiling. In this paper, we describe a dual-wavelength speckle interferometry system using a long working distance (LDM) zoom module for 3D surface shape measurement on a complex sample with combined smooth and rough specimens. For phase extraction at each wavelength, we use higher-order phase shifting algorithm to yield noise reduced phase maps [20, 21]. The experimental results for 3D surface profiling of small scale smooth-rough specimens are presented.

2. DUAL-WAVELENGTH MICROSCOPIC INTERFEROMETRY AND INSTRUMENTATION

Figure 1 represents the schematic a dual-wavelength interferometry system with He-Ne (λ_1=632.8 nm) and frequency doubled Nd:YAG (λ_2 = 532 nm) lasers. Both the beams are expanded and collimated using a spatial filtering setup and a collimating lens. An iris can be used in front of the collimating lens to adjust the size of the collimated beam if needed. The variable neutral density filters (NDF) in the optical setup helps to control intensity of the object and reference beams individually. Shutters can be used in front of the lasers to switch over from one wavelength to other wavelength if sequential illumination is used. The collimated laser beam illuminates the test specimen with smooth-rough surface and a reference mirror via a cubic beam splitter (BS) simultaneously. The smooth-rough microspecimen is mounted on a three-axes translation stage for alignment under the microscope. The microscopic imaging system consists of a long working distance microscope (LDM) with adjustable zoom. The object beam from the specimen and the smooth beam from the reference mirror for each wavelength are recombined coherently onto the CCD plane via the same beam splitter and the microscopic imaging system. From the rough surface, the system records speckle pattern and while from the smooth surface, a visible fringe pattern recorded [2]. The CCD camera acquires the images at different wavelengths. The PZT driven reference mirror is used for introducing the phase shifts between the object and reference beams. It is calibrated for introducing known phase shift. The process of image acquisition with phase shifting at each wavelength is carried out with the support of software. And image processing, phase calculation, and unwrapping are done in software.

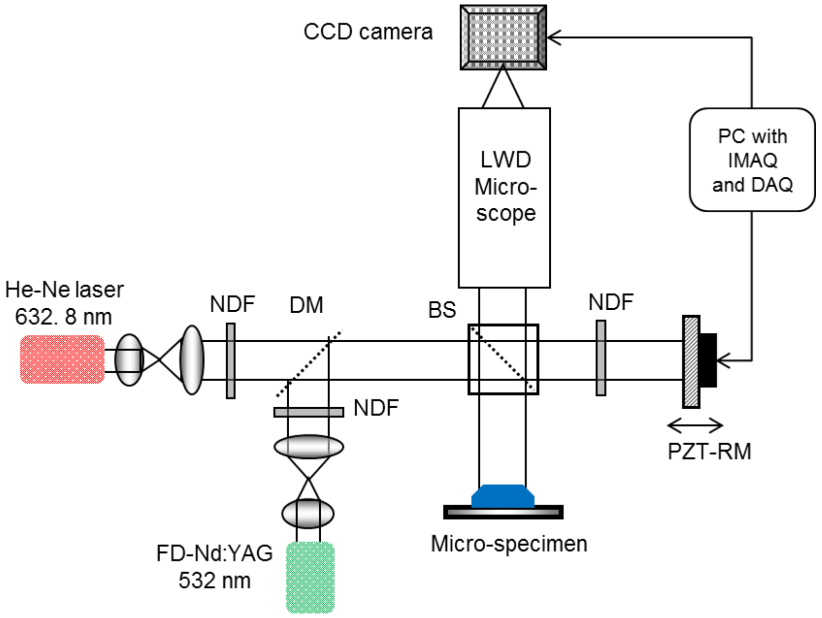

Fig. 1. Dual-wavelength interferometry for surface shape measurement: NDF- neutral density filter, DM- Dichroic mirror, BS- Beam splitter, PZT-RM- Reference mirror mounted on a PZT, LWD- Long working distance, DAQ- Data acquisition card, and CCD- charge-coupled detector .

3. THEORITICAL BACKGOUND FOR MEASUREMENT OF SHAPE USING TWO WAVELENGTHS

Interferometers are widely used in industry for the measurement of shape and deformation on engineering samples with size ranging from millimetre to micro or nanometre. Interferometer, by incorporating different techniques, can be used to inspect both optically smooth and rough surfaces in wide range of sizes [22-24]. The optical inspection can be done under static, quasi-static or dynamic conditions [25-27]. If the test surface is optically smooth, the interference between reference and test beam results in visible fringes. If the test surface is optically rough, the interference results in random speckles. The interferometry that can study rough or diffused surfaces is known as speckle pattern interferometry. In any interferometry, the desired information about the test surface is encoded in the fringe pattern. In fact, the fringe pattern itself represents the phase distribution. The fringe or phase analysis gives the parameters of interest (deformation, phase, etc.) relating to the surface.

Temporal phase shifting technique which requires at least three frames is widely used because it can provide quantitative information with high accuracy [28, 29]. Also there are several single-frame methods where only a single frame or multiple frames in one go are recorded and analysed for phase by an appropriate procedure. The interested reader can find more details on single-shot methods in the Ref.[30-32]. Single-wavelength (1λ) measurements are accurate, but using 1λ-interferometer greatly limits the measurement range and wide spread applications of interferometry. The major drawbacks associated with 1λ-interferometer are it cannot reveal the shape of a rough surface in out-of-plane configuration and it cannot resolve the discontinuities between smooth and rough surfaces. By adding one more wavelength, these problems associated with single-wavelength analysis can be easily solved [33-36].

Implementing multiple-wavelength technique requires more than one wavelength and phase shifting technique requires three or more frames. So, the intensity distribution in the N^th^ phase shifted frame at wavelength λ_i is can be expressed as

$$I_{iN} = I_o(1 + V\,cos[\,\phi_i + (N-1)\alpha_i]) \tag{1}$$

where α_i is the phase shift at λ_i. For monochromatic illumination, if the phase shift is chosen as π/2 the phase can be evaluated using phase shifting algorithms such as 3-step, 4-step, and so on 8-step algorithm. As the number of steps increase, the algorithm becomes less sensitive to phase shift errors [37].

Once phases ϕ_i at different wavelengths are calculated using phase shifting algorithm (8-step algorithm), they can be subtracted to generate synthetic wavelength phases. If ϕ_1 and ϕ_2 are the phases at two different wavelengths, λ_1 , and λ_2 the phases at synthetic wavelength can be generated by using the following equation [38]

$$\phi_2 - \phi_1 = \frac{4\pi}{\Lambda} z \tag{2}$$

where $\Lambda = \lambda_1\lambda_2/|\lambda_1 - \lambda_2|$. Note that due to *arctan* (*tan*$^{-1}$) function used during phase calculation, the phases ϕ_1 and ϕ_2 are wrapped between $-\pi$ to $+\pi$. The phase at synthetic wavelength reveals the shape of the smooth and rough surface under study. If single wavelengths say λ_1 = 632.8 nm, and λ_2=532 nm are used for measurements, then the synthetic wavelength that can be generated is Λ = 3339.8 nm. Thus the interferometry sensitivity is reduced to Λ/2 per fringe.

4. EXPERIMENTAL RESULTS

As mentioned in Section 3, for rough surface the interference is between a scattered beam with a smooth beam, hence no fringe patterns are visible due to random speckle background, while for smooth surface one can observe the interference pattern. We have studied a rough-smooth micro-specimen for dual wavelength analysis which had a rough surface (right) and smooth surface (left). Figure 2(a) and Figure 2(b) are CCD recorded patterns at λ_1= 632.8 nm and λ_2= 532 nm respectively. From these images, it can be seen that in the rough region, no visible fringes are observed; on the other hand one can clearly see fringes in the smooth region. For 3D surface shape measurement, phase shifting technique is used. For incorporating the phase shifting, initially the PZT was calibrated for known phase shift. Multiple phase shifted frames were recorded at each wavelength. Interference phase at each wavelength is calculated using error-compensating phase shifting algorithm. The phase maps (ϕ_1 and ϕ_2) evaluated at λ_1= 632.8 nm and λ_2= 532 nm are shown in Figure 3(a) and Figure 3(b) respectively. Now these two phases are subtracted using Equation (2). When the wrapped phase at λ_1= 632.8 nm is subtracted from the wrapped phase at λ_2 = 532 nm, the result is again a wrapped phase map at effective wavelength. The effective wavelength phase map at Λ = 3339.8 nm is shown in Figure 3(c). Here each fringe corresponds to $\Lambda/2$. In Figure 3(c), one can now observe the phase fringes in the rough surface region. Thus two-wavelength phase subtraction method reveals the contour fringes on a rough surface. The subtracted phase is then unwrapped using conventional 2D unwrapping algorithm. The unwrapped continuous 2D phase of the sample is shown in Figure 4(a). This phase is then quantified using the out-of-plane relation $z = (\Lambda/4\pi)\ (\phi_1 - \phi_2)$, where Λ-effective wavelength, (ϕ_1 - ϕ_2) – phase difference between single wavelength phases, and z- surface profile height or depth. The 3D view of the sample with smooth-rough surface is shown in Figure 4(b). Thus the rough and smooth surface shape is reconstructed and the discontinuity between them is also resolved using the dual wavelength synthetic wavelength approach. This approach can be used for large deformation measurements and simultaneous measurement of shape and deformation on rough samples.

5. CONCLUSIONS

In this paper, we discussed a dual-wavelength phase shifting interferometry for high-resolution 3D surface profiling of a micro-sample. A composite sample with rough/smooth surfaces on a single flat-form is investigated to show the function and reliability of the dual wavelength phase subtraction approach. Single wavelength phase of the sample surface is calculated using an accurate phase shifting algorithm. And the resultant single-wavelength phases are digitally subtracted to generate synthetic wavelength phase. This approach could resolve the rough surface shape as well the discontinuity between the smooth and rough surfaces. It can also increase the measurement range of a single-wavelength interferometry. This study will find will applications in 3D surface profiling of microsystems.

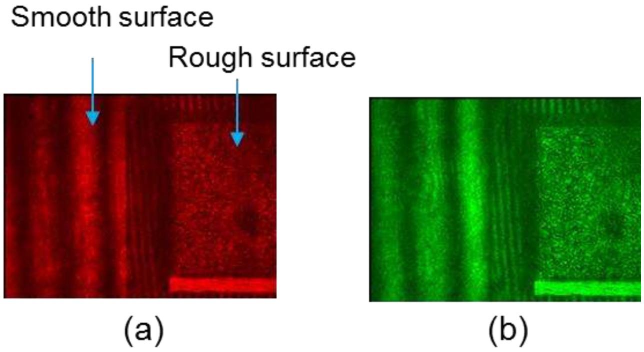

Fig. 2. Interference fringes generated on a combined smooth and rough surface: (a) Interferogram at 632.8 nm, (b) Interferogram at 532 nm. Fringes are visible on the smooth region. No visible fringes are seen on the rough surface region due to random speckles.

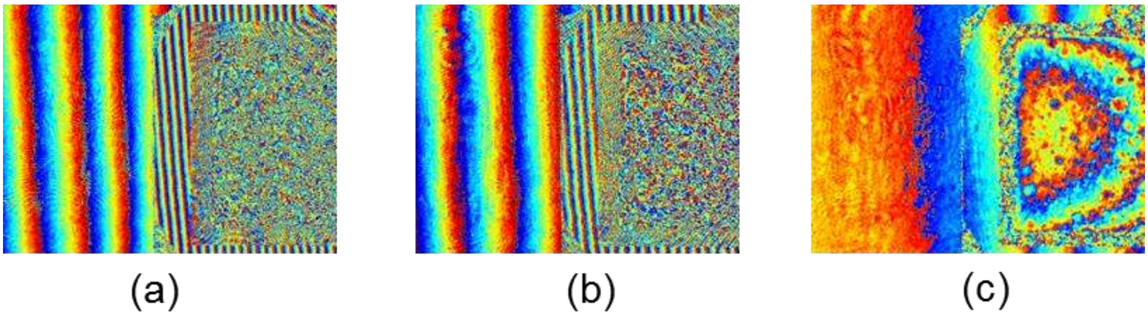

Fig. 3. Synthetic wavelength analysis for contouring: (a) wrapped phase map at 632.8 nm, (b) wrapped phase map at 532 nm, and (c) wrapped phase map at synthetic wavelength 3339.8 nm obtained by subtracting the single wavelength phases. The phase is wrapped between $-\pi$ to π due to *arctan* function. Fringes are visible on the phase at synthetic wavelength shows the contour fringes of the rough surface.

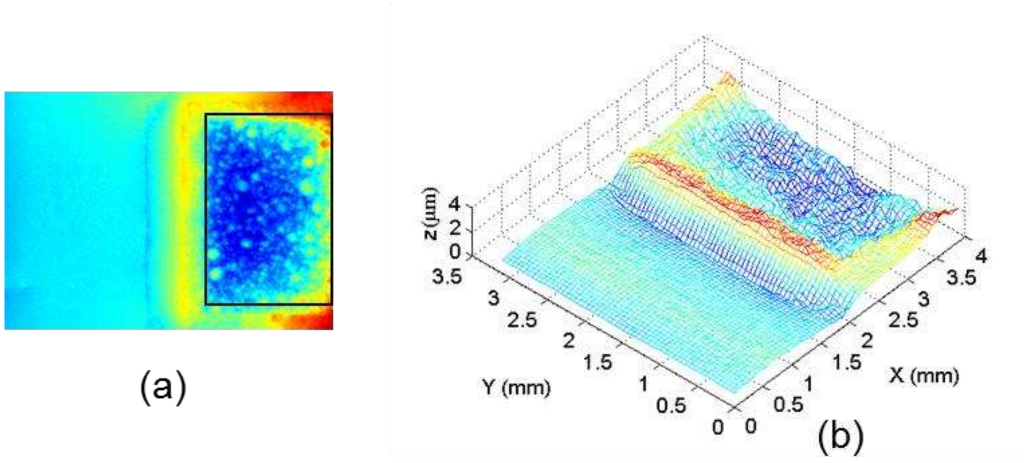

Fig. 4. 3-D contour plot of a rough-smooth surface using synthetic wavelength analysis: unwrapped phase map of the sample (left), and 3-D view of the sample (right). The rough surface shape and step between smooth/rough surfaces are quantified.

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