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Pixelated pattern illumination for chromatic focus variation microscopy: enabling specular surface measurement

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Abstract

Optical surface metrology instruments are designed based on a specific single operation principle that only allows surfaces of a certain surface texture scale to be measured. For example, a focus variation (FV) microscope can only measure rough surfaces that have sufficient texture; hence, it fails to measure smooth surfaces because there is limited contrast between adjacent pixels. This paper proposes a method to measure a wide range of surface features with different length scales using a single unique optical setup based on the FV concept. In addition to rough surfaces measured already with the FV microscope, this paper enables smooth surface measurements by projecting an illumination pattern on the measured surface where a contrast difference is generated between the adjacent pixels. There is no electrical power required to generate the projected pattern nor mechanical scanning to shift the focal plane. The experimental results show that the proposed setup can successfully measure a smooth 1.2 µm step height sample.Focus variation, Specular surface measurement, Pixelated mask.

1. Introduction

Focus variation (FV) instruments are widely used in the industry due to their ability to measure steep and high-slope surfaces. Their method is based on capturing images at different scanning positions, forming a stack of images and analysing the contrast between the neighbouring pixels to determine the image focus position and extract the surface map. FV systems only measure rough surfaces but fail to measure smooth/specular surfaces, i.e., those with insufficient texture under a microscope, such as mirrors, silicon wafers, or additively manufactured surfaces, where highly reflective smooth regions appear with rough regions.

The problem of having both smooth and rough surfaces is present in many products in the industry, and it was found that stochastic surfaces with contaminants/impurities present cannot be characterised by a single measurement technique. For example, defects can be measured by a focus variation instrument but with a large amount of missing data across the surface. On the other hand, interference instruments can successfully measure the surface but with missing data at the defect. For this reason, manufacturers need large investments in metrology equipment to inspect surfaces with features at different scales. Therefore, it is crucial to evolve the metrology instrumentation to retrieve the full surface efficiently using a single optical setup.

In previous research, the authors developed a chromatic focus variation (CFV) microscope [1] that utilises optical scanning, i.e., shifting focal positions of the light beam along the optical axis by changing the wavelengths. This approach brings significant enhancements in measurement speed and reduces the instrument size for on-machine metrology tasks. The CFV works with the same FV concept to measure rough surfaces; however, it fails to measure smooth/specular surfaces, i.e., those with insufficient texture under a microscope, such as mirrors, silicon wafers, or additively manufactured surfaces, where highly reflective smooth regions appear with rough regions.

To generate enough contrast on smooth surfaces to be measured with the FV system, many researchers proposed the projection of artificial texture on smooth surfaces using different techniques. Noguchi and Nayar [2] used an optical filter placed in front of the light source to produce a chessboard illumination pattern on the smooth surface. Because of the limited manufacturing tools at that time, the pattern size was 26 µm x 22 µm. This size was able to produce a contrast difference in the captured images, but the surface measurement had less spatial resolution because of the low frequency of the illumination pattern.

Tiantian and Hongbin [3] developed a method that combines steerable filters with blur estimation to provide better assessment of focus position for those texture-less regions. Bermudez et al. [4] introduced an Active illumination Focus Variation (AiFV) by utilising a microdisplay to generate a 3.6 µm chessboard illumination pattern installed on a confocal microscope using a 20x objective lens. In a recent article, Chen and Chen [5] used a similar concept by employing a digital micromirror device (DMD) to produce digitally controlled patterns on smooth surfaces. All of the above systems utilise mechanical scanning mechanisms for image acquisition.

This paper proposes an illumination pattern via a polarised pixelated phase mask placed in front of the light source to enable the measurement of optically smooth surfaces with the chromatic focal shifting mechanism. The illumination produces a high-density pixelated pattern (e.g. 7.4 µm pixel pitch) with no power or control requirements, as seen in microdisplay and DMD. Such phase mask was initially introduced for a phase-shifting interferometer [6], but here, it is utilised in the CFV system. The polarised mask is made of a micropolariser array, which is fabricated using advanced lithography techniques on a glass substrate of 4.9 x 3.7 mm and 0.7 mm thickness [6].

2. Proposed system

The pixelated mask unit was added to the CFV system setup shown in Figure 1, which integrates the pixelated pattern projection (the green box) into the CFV setup in a single optical setup. With the help of the acoustic-optic tunable filter (AOTF), the wavelength was swept from 530 nm to 590 nm, resulting in a 40 µm scanning range using the 20x dispersive objective lens. An image was captured every 0.3 µm, with a total of 128 images captured. The focal shift at each wavelength was determined prior to the measurement by scanning the focal spot with a PZT stage and identifying the position with the best image contrast, based on the MTF concept. The 128 images are obtained at different focus positions, and the image stack was used to extract a focus measure profile [7] to estimate the best-focused position and generate the surface topography.

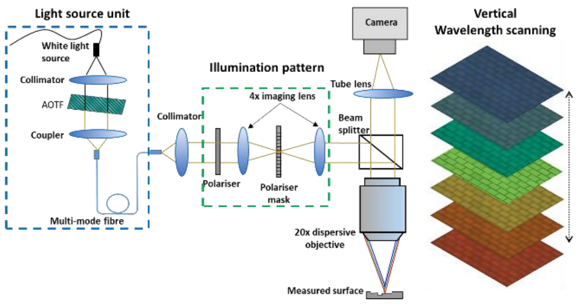

Figure 1. Schematic of CFV adapted from [1] with modification of the pixelated pattern illumination.

The pixel pitch of the polarised mask is 7.4 µm, with standard transmission axis (0°, 45°,90°, and 135°) providing different polarising statuses and intensity levels (white, grey, black). The mask was placed at the focal distance of two 4x Nikon lenses with a 0.13 numerical aperture (NA) and a 17 mm working distance. A polariser was placed before the mask unit to control the pattern orientation as needed. Figure 2 shows the experimental setup using the pixelated mask projection.

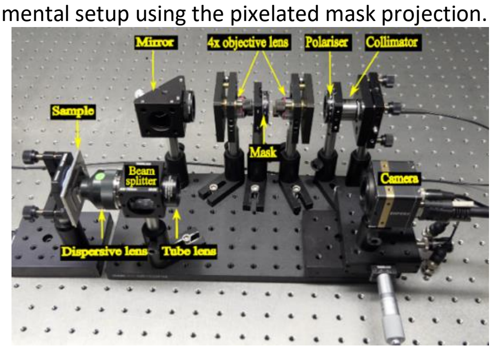

Figure 2 Chromatic focus variation setup with a mask pattern projection.

Figure 3 shows a mirror surface before and after projecting the mask pattern, where the pixelated pattern replaced the smooth surface.

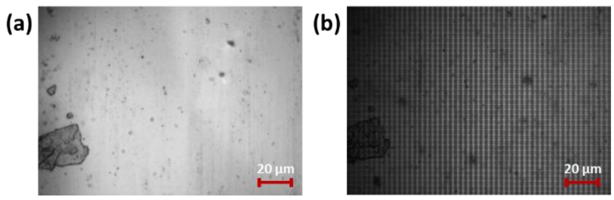

Figure 3. Mirror surface. (a) No mask projection, (b) With mask projection.

3. Results and discussions

An experiment was performed to test the proposed system by projecting the pixelated pattern alongside the focal shifts during the wavelength scanning process to measure a 1.2 µm step height on a smooth surface with 3 nm roughness. Traditionally, the FV system cannot identify the step height. However, the proposed system successfully measured the step height, as shown in the areal and profile measurements in Figure 4. The step height obtained using the Bruker Contour interferometer and the CFV system was found to be 1.2 µm and 1.8 µm respectively, suggesting an error of 0.6 µm.

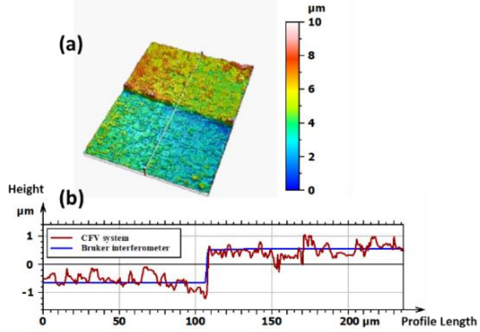

Figure 4. 1.2 µm step height measurement. a) Areal. b) Profile.

The noise in the results can be linked to the dispersive lens quality, as discussed in [1]. Better measurement resolution can be achieved by correcting unwanted aberrations in the dispersive lens.

4. Conclusion

The focus variation method is applicable for textured surfaces using the contrast difference between neighbouring pixels, but the method fails when measuring smooth/specular surfaces. This paper enables the FV method to measure optically smooth surfaces by projecting an artificial texture using a polarised phase mask on the light source. The projected pattern creates the required contrast for detecting the focus positions and determining the surface topography. Further analysis will be considered with a second version dispersive lens to eliminate the errors introduced by aberrations existed in the current lens.

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