DOE-based Multi-spot Confocal Interference Microscope

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Abstract

Diffractive lens arrays are used to enhance the resolution of a low-numerical-aperture objective to perform high-resolution large-area measurements. However, the axial resolution of such setups is still fundamentally limited by the objective[4]. This work introduces the concept of utilizing the reflected conjugate wave of the diffractive optical elements (DOEs) for interference measurements. A traceable step height target is measured and the experiment result shows that the proposed setup can improve the accuracy and reduce the measurement uncertainty in the axial direction.

1 Introduction

Nowadays, with the development of nanotechnologies, there are more and more needs for precise measurement of the small surface structures over a large area, such as semiconductor wafers and meta-surfaces. Confocal microscopy has always been one of the most commonly used methods for surface measurements. It can provide high resolution while being contactless and easy to use. However, microscope objectives have the trade-off between resolution and field of view

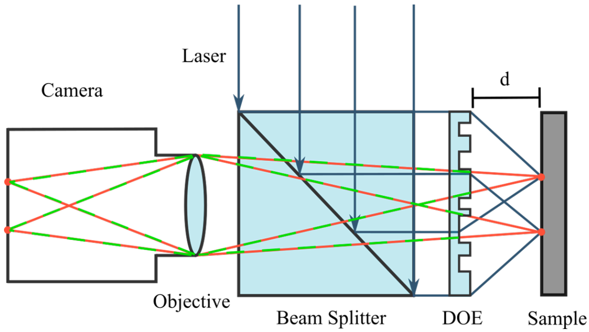

Figure 2.1: Setup of the DOE confocal interference microscope.

(FOV). High-resolution objectives with high numerical apertures (NAs) also have high magnifications, which lead to limited FOVs.

In the previous researches, diffractive lens arrays have been proposed to increase the FOVs of the confocal microscope objectives while maintaining high lateral resolution [3, 6, 5]. Unlike the traditional micro-lens arrays, they no longer have the restrictions between the pitches and the NAs of the micro lenses. They can produce highly focused spots in a dense grid over a large area. Combined with low-NA objectives, large-area measurements with high lateral resolution become possible. However, such setups also have some drawbacks. The axial resolution in this case is still limited by the low-NA objectives.

To overcome such limitation and reduce the axial measurement uncertainties, the idea of interference is utilized. As one of the most precise distance measurement techniques, interference can improve the axial resolution of the previous DOE based confocal microscopes. The concept for the proposed setup will be explained in the next sections. Experiments of a traceable step height target are also carried out to demonstrate such improvements.

2 Confocal Interference Microscope

Figure 2.1 shows the concept of the DOE based confocal interference setup. In the setup, a high-coherence light source, i.e. a collimated laser, is reflected by a beam splitter and illuminates the DOE. Under the plane-wave illumination, the DOE will produce multiple tiny spots with high NAs on the sample surface. These spots will be reflected by the sample as the probe beam, which is shown as red lines in Figure 2.1. At the same time, the DOE will reflect a certain amount of light back as the conjugate wave of the focused spots. The conjugate wave is represented by the green lines in Figure 2.1, which becomes the reference beam. The reflectance of the DOE is determined by the material itself, which is around 4% for fused silica at an incident angle of $90°$ and can be further controlled by a coating.

An objective collects the probe beam and the reference beam and forms an image on the camera sensor. When a surface is placed on the focal plane, the two beams produce two sets of spots in the image, which is shown in Figure 2.2a. Note that the yellow spot is from the direct reflection of the plane surface, which should have the same phase as the probe beam and will not overlap with spots for a sample placed with an angle. By mechanical alignment of the positions of the beam splitter, the objective and the DOE in the setup, the reference and probe spots shown in Figure 2.2b can superimpose with each other perfectly, which means that the reference and probe beams overlap with each other perfectly. Thus the reference and probe beams will interfere with each other. In this case, if the distance between the DOE and the sample is defined as d, then the phase shift for the interference between the probe beam and the reference beam is $4\pi d/\lambda$.

With such a setup, when the surface is scanned axially, interference will occur between the reference and probe beams. Interference fringes can be observed on a confocal peak like modulation signals on a carrier wave. Experiments are shown in the next section for demonstrating such phenomena. It will also be applied in measuring a step height target to reduce the axial measurement uncertainty.

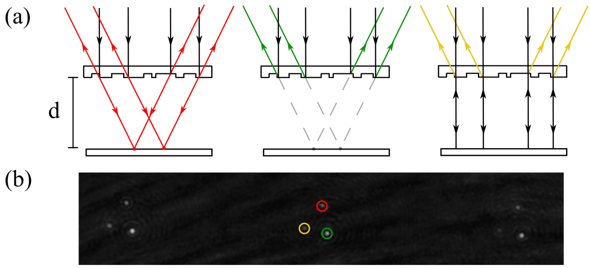

Figure 2.2: Reflection from the DOE and the sample surface. (a) Focusing wave, reflected conjugate wave and reflected wave by the plane surface. (b) Spots from different waves when a piece of glass is placed underneath the setup.

3 Experiment results for surface measurement

For proof of the concept, a testing setup is built as Figure 3.1 shows. A $50\,\mathrm{mW}$ volume-holographic-grating single-frequency $785\,\mathrm{nm}$ fiber-coupled diode laser from Thorlabs is collimated by an objective through a beam splitter. The collimated plane wave illuminates the DOEs, which focuses the illumination into a spot array. The probe beam reflected by the surface and the reference beam reflected by the DOE is collected by the objective and they are imaged onto the camera sensor by the tube lens.

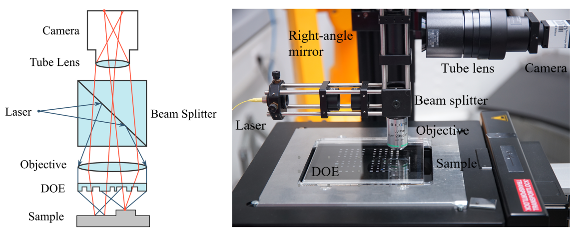

Figure 3.1: Experiment setup of the DOE-based confocal interference microscope.

A traceable step height standard target (VLSI SHS-9400QC) is placed underneath the DOE as the sample to test the measurement uncertainties. The target is shown in Figure 3.2a. There is a convex bar precisely produced by lithography with a width of $100\,\mu\mathrm{m}$ and a calibrated height of $925.5 \pm 5.4\ \mathrm{nm}$. Height measurement of the bar follows the procedures of VLSI [7, 2]. Three lines are measured along the cross section of the bar, which are represented by A, B and C in Figure 3.2b. The length of each line is a third of the width of the bar.

Three adjacent spots in the 11×11 spot array with a pitch of $100\,\mu\mathrm{m}$ produced by the DOE are scanned axially to measure the height of the bar. The DOE has a working distance d of $1\ \mathrm{mm}$. A typical confocal interference signal of a single spot is shown in Figure 3.3a. Interference fringes with oscillation can be observed in the figure. Please note that the fringes disappear on the edge because the axial sampling is set to a larger value to save the measurement time. The highest peak of the signal is fitted by a polynomial and the height is calculated. In this way, each line is sampled with a step of $3\,\mu\mathrm{m}$ in the x direction in Figure 3.2. Afterwards, all the lines are fitted by the following equation [1]

$$z = \begin{cases} ax + b_1, & x \in (A, B), \\ ax + b_2, & \text{otherwise}, \end{cases} \tag{3.1}$$

where z is the measured height, x is the lateral position and a, b_1 and b_2 are the line fitting parameters. The height of the bar h is thus derived as

$$h = \frac{b_2 - b_1}{\sqrt{a^2 + 1}}. \tag{3.2}$$

The measurement is repeated 10 times in the y direction along the bar with a step of $10\,\mu\mathrm{m}$. The bar height at each y position are calculated. The mean value

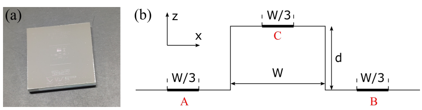

Figure 3.2: VLSI SHS-9400QC step height standard calibration target. (a) Picture of the target. (b) Cross section of the measurement area.

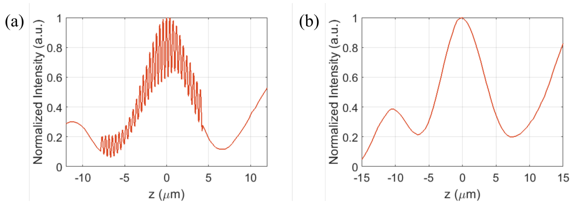

Figure 3.3: Axial measurement signal with a $20\times$ 0.5 NA objective. (a) Confocal interference axial response of a single-frequency laser. (b) Confocal axial response of a laser with a bandwidth of $2\,\mathrm{nm}$.

of the measured height is $904.7\,\mathrm{nm}$ with a standard deviation of $9.7\,\mathrm{nm}$. For comparison, another $785\,\mathrm{nm}$ diode laser from Thorlabs with a larger bandwidth of $2\,\mathrm{nm}$, which has a much shorter coherence length of around $0.3\,\mathrm{mm}$, is used for pure confocal measurement. A typical signal can be seen in Figure 3.3b. Note that the asymmetrical peak shape is due to the aberration of the objective when imaging through the DOE glass, which has a thickness of $6\,\mathrm{mm}$. The confocal measurement has a mean value of $965.5\,\mathrm{nm}$ with a standard deviation of $40.3\,\mathrm{nm}$. It is obvious that the interference measurement significantly reduces the measurement uncertainty.

The measurement error is mainly due to the noise caused by the stray light. The stray light comes from different aspects, such as reflection from the unmatched coating of the objective and other diffraction orders due to the low diffraction efficiency of the binary phase mask. The measurement uncertainty can hopefully be further reduced by changing the objective coating or a multi-level phase mask which has a much higher diffraction efficiency.

4 Conclusion

Microscope objectives with high resolution usually have small FOVs. Diffractive lens arrays can keep both the high lateral resolution and the large FOVs of low-NA objectives in confocal microscopy. However, the axial resolution of such setups are still limited by the low-NA objectives for surface measurement.

This work uses the originally wasted reflected conjugate wave of the DOEs to make interference measurements to increase the axial resolution of previous setups. Experiments are carried out with a calibrated step height target which has a certified height of 925.5 ± 5.4 nm. The interference measurement show a result of 904.7 nm with a standard deviation of 9.7 nm. Compared to the solely confocal measurement, which has a result of 965.5 nm with a standard deviation of 40.3 nm, the measurement uncertainty is clearly reduced and the accuracy is increased.

In the future, a new DOE with higher NAs will be produced to further test the resolution limit of the diffractive lens arrays. New experiment setup will be built and the application will be extended to other fields, for example, fluorescence microscopy.

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