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Correction of phase drifts in two-wavelength digital holographic microscopy using secondary reference waves

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Abstract. We present a two-wavelength digital holographic microscopy setup for surface topography measurement with single-point illumination and a method for correction of unwanted phase drifts using secondary reference waves.

1 Introduction

Digital holographic microscopy (DHM) is one of the modern methods for optical measurement of surface topography [1]. In the off-axis configuration, interference between an object wave reflected from the specimen and a tilted reference wave generates a fringe pattern detected by the camera as a digital hologram. Evaluation based on a two-dimensional Fourier transform allows for the calculation of the interference phase and the specimen height profile [2]. Using two different wavelengths and the corresponding synthetic wavelength, large height steps can be measured [3] as well as large specimens that require stitching of multiple overlapping areas [4]. However, most of the existing DHM setups with plane wave illumination are designed for optically smooth surfaces.

In this paper, we present an off-axis two-wavelength DHM setup based on single-point illumination by a focused Gaussian beam, which is intended for surface topography measurements of both optically smooth and rough specimens. The measurement points are spatially separated as with other point instruments [5, 6], so the temporal stability of the interference phases is crucial. Since the object waves and the primary reference waves are delivered by polarization-maintaining (PM) fibres, we propose a method based on secondary reference waves to correct for unwanted phase drifts caused by fluctuations in temperature, wavelength and polarization. We describe the theoretical principles of the phase correction method as well as experimental results.

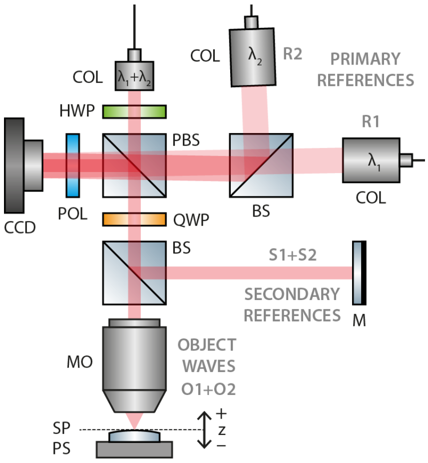

Figure 1. Experimental setup: collimator (COL), $\lambda/2$ plate (HWP), polarizing beam splitter (PBS), beam splitter (BS), $\lambda/4$ plate (QWP), microscope objective (MO), specimen (SP), positioning system (PS), polarizer (POL), digital camera (CCD).

2 Principles

The optical setup shown in Fig. 1 used two monochromatic laser beams with close wavelengths λ_1, λ_2 coupled into a single PM fibre that provides perfectly aligned object waves focused by a high-numerical-aperture microscope objective on the specimen surface. The reflected object waves O_1, O_2 and the tilted primary reference waves

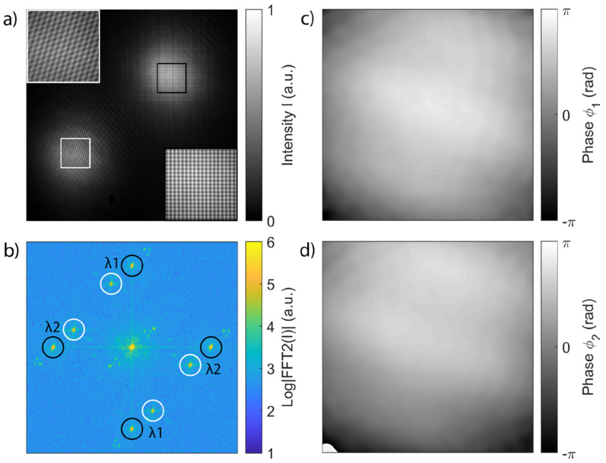

Figure 2. a) Digital hologram, b) frequency spectrum, c) interference phase ϕ_1, d) interference phase ϕ_2.

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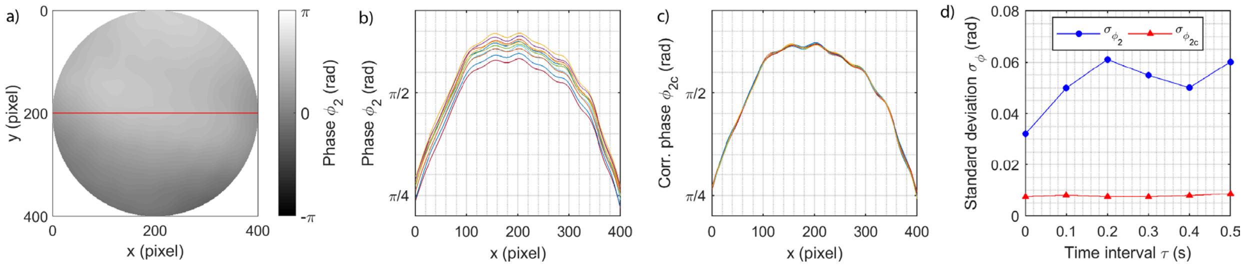

Figure 3. Experimental results for wavelength λ_2: a) phase profile ϕ_2 with central section (red line), b) 10 consecutive profiles of phase ϕ_2 for $\tau = 0.5$ s, c) the corresponding profiles of the corrected phase ϕ_{2c}, d) mean standard deviations σ_{ϕ_2} and $\sigma_{\phi_{2c}}$ depending on τ. Similar results were obtained for wavelength λ_1.

R_1, R_2 provided by separate PM fibres and large-diameter collimators generated two mutually orthogonal sets of interference fringes detected by the camera as a primary digital hologram (see Fig. 2a). An auxiliary beam splitter placed before the microscope objective created secondary reference waves S_1, S_2 that were reflected by a properly tilted auxiliary mirror. The primary and secondary references generated another two sets of mutually tilted interference fringes recorded at the same camera image. This secondary pattern was used to detect the unwanted phase drifts under the condition of balanced optical path lengths for the object waves and the secondary reference waves.

The camera image evaluation using a two-dimensional fast Fourier transform (2D FFT) provided a frequency spectrum in which the individual interference terms were represented by separate peaks (see Fig. 2b). Spatial filtering and inverse 2D FFT of the black-bordered areas yielded the interference phases $\phi_1(x, y)$, $\phi_2(x, y)$ between the object waves and the primary references (Fig. 2c, 2d), containing information about both specimen surface and unwanted phase drifts. The white-bordered peaks provided single value phases ϕ_{1d}, ϕ_{2d} corresponding to the phase drifts. The subtraction yielded the corrected phases $\phi_{1c}(x, y) = \phi_1(x, y) - \phi_{1d}$ and $\phi_{2c}(x, y) = \phi_2(x, y) - \phi_{2d}$ related to the specimen surface only that are applicable to calculate the surface height using the synthetic wavelength with proper continuity between the measurement points.

3 Experiment and results

The phase correction method was tested experimentally using the setup shown in Fig. 1 based on two tunable distributed Bragg reflector (DBR) laser diodes operating at the wavelengths of 631.65 nm and 634.05 nm. As a specimen, a plane mirror was placed in a fixed position close to the focal plane of the microscope objective. Using the digital camera, we acquired 6 sets of 100 images with a predefined time interval $\tau \in \{0, 0.1, 0.2, 0.3, 0.4, 0.5\}$ s between the consecutive images.

The evaluation provided the phase profiles ϕ_1, ϕ_2 and the corrected phase profiles ϕ_{1c}, ϕ_{2c} (see Fig. 3a). For given τ, the central sections of the phase profiles ϕ_1, ϕ_2 plotted in a single graph show a time-dependent drift (see Fig. 3b). The mean standard deviations of phase $\sigma_{\phi_1}, \sigma_{\phi_2}$ calculated along the section line for each data set are relatively high (see Fig. 3d). In contrast, the corrected phase profiles ϕ_{1c}, ϕ_{2c} closely overlap (see Fig. 3c) and the corresponding mean standard deviations of phase $\sigma_{\phi_{1c}}, \sigma_{\phi_{2c}}$ are reduced to relatively low values that are almost independent of τ. These results show that the unwanted phase drifts can be successfully eliminated over long periods.

4 Conclusion

We presented the off-axis two-wavelength DHM setup with single-point illumination and the method for correcting unwanted phase drifts using secondary reference waves. The experimental results showed that the phase drifts can be eliminated even for measurements over a long period of time, providing the crucial stability of the interference phases required for topography measurements at multiple spatially separated points on the specimen surface.

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