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Common-path interferometer with four simultaneous phase-shifted interferograms using ronchi grating and cube beamsplitter

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ABSTRACT

A common-path interferometer is built using a 4*f* optical system with a ronchi ruling used as a spatial filter and a cubic beamsplitter used as an interferogram duplicator. The input aperture is divided into two windows to support the orthogonal circular polarized reference and object beams. Four phase shifted interferograms modulated by polarizing filter array can be captured simultaneously in the output plane. Because the four interferograms have the same fringe visibility, a standard four step algorithm can be used to reconstruct the phase of a sample. The validity and stability of the proposed interferometer in achieving four simultaneous phase-shifted interferograms is proved through experiments.

1. Introduction

Phase-shifting interferometry (PSI) is a noninvasive, high precision and full field technique used for measurement of surface profile, transparent specimen thickness or index [1–3]. In the conventoinal PSI, at least three phase-shifted interferograms are sequentially acquired by driving a mirror or grating. This may not be suitable for a simultaneous measurement of moving objects or dynamic processes. Phase noise may increase due to system fluctuations between frames. Different simultaneous phase-shifting interferometers [4–9] are proposed to overcome this drawback by recording phase-shifting interferograms in one shot. Compared to separated-path PSI [4–6], common-path PSI, such as point diffraction interferometer [7,8] and common-path Fizeau interferometer [9] is less affected by environmental disturbance because both the object and reference waves pass through the same optical path. However, these common-path PSIs need such special elements as pinhole with carefully chosen diameter or quarter wave plate with high quality reflection layer. A two-window common-path interferometer with simultaneous phase-shifting [10–15] has been proposed recently, it includes two windows in the object plane of a 4f system and a grating in the Fourier plane and uses polarization elements to achieve phase shifting. This interferometer can realize high stability and low noise real-time measurement. However, the fringe visibilities of the phase shifted interferograms recorded in one shot are different because the interferences are based on superposing different diffraction orders. Such complex operations as normalization on these interferograms are therefore required to reconstruct the phase of a sample. In addition, some of these interferometers require one-dimensional phase grating or even more complex two-dimensional phase grating/grids. However, a more common ronchi grating is expected to be used in the interferometer because the diffraction efficiencies for diffraction orders ± 1 and 0 are good enough to display adequate interferograms. Although a ronchi grating has been introduced by Meneses-Fabian et al. [15] into the two-window common-path interferometer, an actuator is still required for driving grating to achieve phase shifting.

In this paper, a common-path simultaneous phase-shifting interferometer is proposed by introducting a cube beamsplitter into the two-window common-path interferometer. Four phase shifted interferograms with the same visibility are obtained in one shot, and a standard four step algorithm can be then used for the reconstruction of the phase map. Some experiments are shown to demonstrate the validity and stability of the proposed interferometer.

2. Experimental setup

As shown in Fig. 1, this setup is arranged to be a standard 4*f* optical image system. Lenses L1 and L2 with focal length *f* are used to execute Fourier transform. The light coming from a nonpolarizing He–Ne laser source with wavelength λ is linearly polarized by polarizer P through 45° with respect to the horizontal axis, and then collimated and expanded by collimator & expander (CE). In

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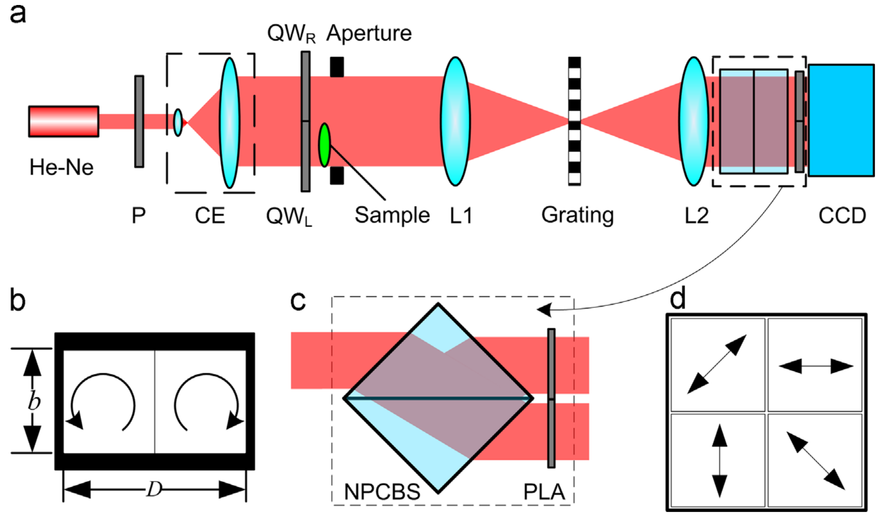

Fig. 1. (a) Experimental setup; (b) Polarization states of the two windows; (c) Side view of NPCBS; (d) Polarization states of PLA. P, polarizer; CE, collimator & expander; QW$_R$, QW$_L$, quarter-wave plates; L1, L2, Lenses; b, D, sides of aperture; NPCBS, non-polarizing cube beamsplitter; PLA, polarizing filter array.

the input plane, the aperture with sides D and b is split into two identical windows, with size $D/2 \times b$ each, to support the reference and object beams. Two quarter-wave plates QW$_R$ and QW$_L$, oriented 0° and 90° along the horizontal axis respectively, are inserted into the front of the two windows to transform the linearly polarized beam into orthogonal circular polarized object and reference beams. Sample is placed before the object aperture. A ronchi grating is placed in the Fourier plane as a spatial filter, and a non-polarization cube beamsplitter (NPCBS) is placed before the CCD camera with its semi-reflecting layer parallel to the propagation direction of incident beams to split the incident beams into two replications by transmission and reflection. A CCD camera is properly placed in the output plane. Four interferograms with different phase shifts are modulated by polarizing filter array (PLA) and then captured by the CCD camera in one shot.

2.1. Fringe visibility analysis

In the two windows interferometer, the interferograms are generated by superposing adjacent orders. Thus, the fringe visibility of each interferogram is affected by the diffraction efficiency of each order. Since the ronchi grating is used as a spatial filter in the fourier plane, the corresponding impulse response $g(x,y)$ [16] in the output plane can be expressed as

$$g(x,y)=\frac{A_w}{d}\sum_{n=-\infty}^{\infty}\exp\left(-i2\pi n\frac{u_0}{d}\right)\mathrm{sinc}\left(n\frac{A_w}{d}\right)\delta\left(x-n\frac{\lambda f}{d},y\right)$$
$$=\sum_{n=-\infty}^{\infty}C_n\delta\left(x-n\frac{\lambda f}{d},y\right) \quad (1)$$

with

$$C_n=\frac{A_w}{d}\exp\left(-i2\pi n\frac{u_0}{d}\right)\mathrm{sinc}\left(n\frac{A_w}{d}\right), \quad (2)$$

where A_w and d are the width of a clear band and the period of ronchi grating respectively; u_0 is the lateral displacement of ronchi grating with respect to the original point along horizontal axis; C_n is the complex coefficient of order n. The fringe visibility V of interferograms can be written as

$$V=\frac{2|C_n||C_{n+1}|}{|C_n|^2+|C_{n+1}|^2}=\frac{2\mathrm{sinc}\left(n\frac{A_w}{d}\right)\mathrm{sinc}\left[(n+1)\frac{A_w}{d}\right]}{\mathrm{sinc}\left(n\frac{A_w}{d}\right)^2+\mathrm{sinc}\left[(n+1)\frac{A_w}{d}\right]^2} \quad (3)$$

In order to make full use of the field of view of a CCD camera, it is generally expected that no more than four interferograms are

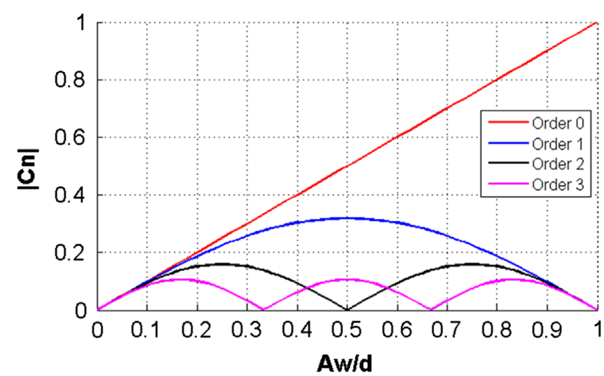

Fig. 2. Variation of complex coefficient $|C_n|$ with different duty cycle A_w/d of grating.

captured in one shot. For orders diffracted by the grating are symmetrically distributed on both sides of the zeroth order, only orders 0, 1, 2, and 3 are considered in our analysis for simplicity. Fig. 2 shows the variation of complex coefficient $|C_n|$ with different duty cycle A_w/d of the grating. It can be seen that maximums of $|C_n|$ for diffraction orders 2 and 3 are less than 0.2, which means that a higher resolving power of CCD is required for interferogram detection with the risk of introducing larger system noise. In addition, $|C_n|$ is 0 when $A_w/d=0.5$, which then means that one of the most common grating with $A_w/d=0.5$ can not be used in the interferometer proposed by Ref. [11]. Fig. 3 shows the variation of fringe visibility V of interferograms with different duty cycle A_w/d of grating. The interferograms are obtained by superposing adjacent orders, for example, interferograms [0, 1] is obtained by the superposing orders 0 and 1. It can be seen from Fig. 3 that if four interferograms ([−2, −1], [−1, 0], [0, 1] and [1, 2]) are expected to be captured in one shot, as Ref. [11] did, the duty cycle of grating should be approximately 0.65 if the same fringe visibility is expected to obtain more simple operation and higher reconstruction accuracy. It then not only limits the parameters selection of the grating but also increases the requirements of grating fabrication. Moreover, for different amplitudes for different diffraction orders, the involved amplitudes of interferograms are not the same, which can also affect the measurement accuracy. However, the interferometer proposed in this paper only uses 0 and ± 1 orders diffracted by ronchi grating. As long as the two symmetrical ± 1 diffraction orders are of equal value, the two obtained interferograms can have the same fringe modulation, and then,