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Circular carrier squeezing interferometry: Suppressing phase shift error in simultaneous phase-shifting point-diffraction interferometer

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ABSTRACT

Circular carrier squeezing interferometry (CCSI) is proposed and applied to suppress phase shift error in simultaneous phase-shifting point-diffraction interferometer (SPSPDI). By introducing a defocus, four phase-shifting point-diffraction interferograms with circular carrier are acquired, and then converted into linear carrier interferograms by a coordinate transform. Rearranging the transformed interferograms into a spatial-temporal fringe (STF), so the error lobe will be separated from the phase lobe in the Fourier spectrum of the STF, and filtering the phase lobe to calculate the extended phase, when combined with the corresponding inverse coordinate transform, exactly retrieves the initial phase. Both simulations and experiments validate the ability of CCSI to suppress the ripple error generated by the phase shift error. Compared with carrier squeezing interferometry (CSI), CCSI is effective on some occasions in which a linear carrier is difficult to introduce, and with the added benefit of eliminating retrace error.

1. Introduction

Point diffraction interferometer (PDI) [1] is widely used in optical manufacturing and testing [2,3], adaptive optics [4,5], phase microscopy [6,7], etc., due to its simple, self-referencing construction. However, this same, desirable characteristic, makes the introduction of phase-shifting technology difficult. One method of achieving this was provided by Kadono, who constructed a pinhole in a linear polarizer and combined with some polarization optics, to realize a phase-shifting PDI [8]. Later, he developed a second phase-shifting PDI by etching a small pinhole in the electrodes of a liquid-crystal variable retarder, and analyzed the potential errors [9]. And Guardalben analyzed the frame-to-frame intensity changes and alignment distortions of the host liquid crystal [10]. Wyant manufactured a polarization point-diffraction plate (PPDP), which is a pinhole etched into a thin-film half-wave plate by using focused ion beam, and realized phase-shifting with an electro-optic modulator, also, the errors in the alignments and retardances of polarization optics are explained [11]. In these cases, the measurements contain a temporal phase-shifting process, and will be influenced by vibration and so on [12], so some work had been done to achieve real-time measurement. Based on the diffraction properties of a grating and a pinhole, Kwon fabricated a pinhole in a sinusoidal transmission grating to produce three simultaneous phase-shifting interferograms, but it exists intensity consistency error between the interferograms to some extent [13]. Later, by starting with a uniform grid, Millerd, and Wyant et al. created another PPDP by using focused ion beam milling and selectively removing material. By coupling the PPDP with an optical configuration that produces four phase-shifting interferograms on a single CCD sensor, a instantaneous phase-shift point-diffraction interferometer was accomplished [14]. Most recently, Lei Chen et al. set up a similar system, by making a pinhole on the metallic wires layer of a wire grid polarizer, which was combined with a simultaneous phase-shifting system, to realize a spatial phase-shifting polarization interferometer, they also analyzed the diffraction wavefront quality and the retardance error in the system [15].

Most of the systems mentioned above adopted some polarization optics and beam splitters, such as retarders, or gratings. That means the optical axis alignment error, retardance error, etc. may contribute to the phase-shift error [11,16]. Utilizing the iterative method and statistical technique, some algorithms have been proposed to suppress phase-shift error. Qian proposed an iterative method based on least-squares fittings to retrieve wavefront phase from tilt phase-shift interferograms [17], while Yichun worked to overcome the random piston and tilt wavefront errors generated by the phase shifter [18]. Jianxin used Radon trans-

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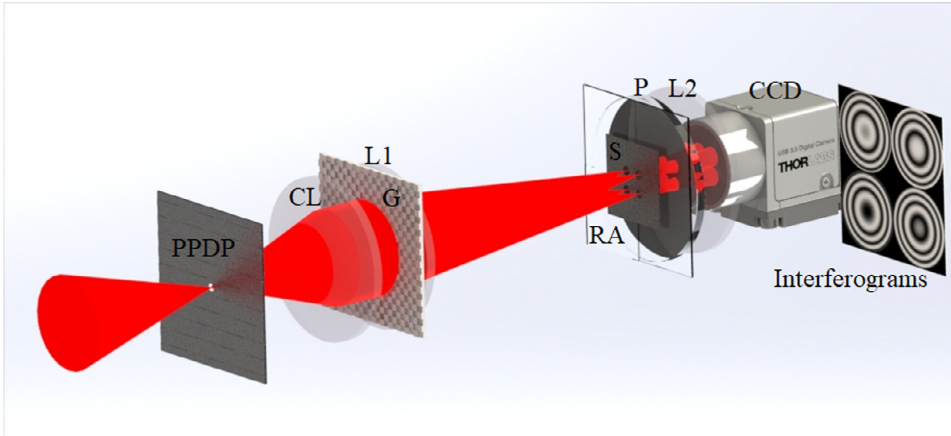

Fig. 1. Diagram of the SPSPDI.

form to extract the phase plane with random tilts, and then retrieved the phase distribution by the least squares method [19]. In contrast, G Lai proposed a generalized phase-shifting interferometry [20], and later, some other scholars improved this method and made some applications. It is a good phase retrieval method for interferograms with random phase-shifts. It can be easily coded without iteration [21–23]. Based on squeezing interferometry [24], Bo Li proposed carrier squeezing interferometry (CSI) to suppress errors from inaccurate phase shift [25], which was later improved by Zhu such that only two interferograms were needed [26]. CSI requires introducing a linear carrier in the interferograms, usually by tilting the reference mirror, which can be difficult when measuring a specimen with large spherical departure or an on-axis asphere with small aspherical departure with a phase-shfting point-diffraction interferometer, because as the focus of the convergent beam deviates from the center of pinhole in the direction perpendicular to the axis, the diffraction beam (reference beam) can't cover the transmission beam (test beam) completely, and it may even generates interferogram between the transmission beam and the first order diffraction ring, these factors will all lead to faulty measurements. But in these situations, circular carrier interferograms are easier to be achieved than linear ones by introducing a defocus in an interferometric setup [2].

In this paper, we propose a circular carrier squeezing interferometry (CCSI) method, and apply it to suppress the phase shift error in a simultaneous phase-shifting point-diffraction interferometer (SPSPDI), the CCSI eliminates the ripple error generated by phase-shift error in phase distribution effectively. It is suitable for some occasions in which CSI is not effective, since tilt is difficult to introduce, for example, phase-shifting point-diffraction interferometers, and also when a specimen with large spherical departure or an on-axis asphere with small aspherical departure is measured. Additionally, there is no retrace error compared to CSI in which a linear carrier is required, usually by tilting the reference mirror, and lead to deviation between reflected light and incident light.

2. Theory

2.1. SPSPDI

As shown by Fig. 1, a convergent beam propagates through a polarization point-diffraction plate (PPDP), which is based on a wire grid polarizer, by manufacturing a pinhole on its metallic wires layer. After a collimating lens (CL), the transmission beam and diffraction beam propagate in parallel to a grating (G), then are focused via a lens (L1), Four diffraction orders with the same diffraction efficiency are selected by a stop (S) at the focal plane of L1, and then pass through a retarder array(RA), which contains four retarders with different retardations of 0, $\pi/2$, π, and $3\pi/2$, respectively, the following is a polarizer (P) and another lens (L2), so we can acquire four simultaneous phase-shifting point-diffraction interferograms.

2.2. Circular carrier squeezing interferometry

In general, the intensity of the n-th interferogram acquired by a phase-shifting interferometer can be expressed by

$$I_n = a(x,y) + b(x,y)\cos\left[\varphi(x,y) + 2\pi f_0 n + \varepsilon_n(x,y)\right], n = 0,1,\ldots,N-1 \tag{1}$$

where $a(x, y)$ represents the background component, $b(x, y)$ is the contrast, $\varphi(x, y)$ is the initial phase, f_0 is the phase shift frequency which equals $1/N$, and $\varepsilon_n(x, y)$ is the phase shift error of the nth interferogram. By Introducing a defocus into the interferogram, a circular carrier interferogram is acquired, and Eq. (1) can be rewritten as

$$\begin{aligned} I_n =\ & a(x,y) + b(x,y)\cos\left[2\pi f_c\left(x^2+y^2\right) + \varphi(x,y) + 2\pi f_0 n + \varepsilon_n(x,y)\right], \\ & n = 0,1,\ldots,N-1 \end{aligned} \tag{2}$$

where f_c is the circular carrier coefficient, and the coordinate of the circular carrier interferogram center is (0, 0) in the Cartesian coordinate system. Choosing the center to be the original point, a coordinate transform is made using the following equations,

$$\begin{cases} x = \sqrt{\rho}\cos\theta \\ y = \sqrt{\rho}\sin\theta \end{cases} \tag{3}$$

The intensity expression of a circular carrier interferogram can be rewritten in the new coordinate system (ρ, θ), as

$$\begin{aligned} I_{Qn} =\ & a_Q(\rho,\theta) + b_Q(\rho,\theta)\cos\left[2\pi f_c\rho + \varphi_Q(\rho,\theta) + 2\pi f_0 n + \varepsilon_{Qn}(\rho,\theta)\right], \\ & n = 0,1,\ldots,N-1 \end{aligned} \tag{4}$$

where $a_Q(\rho, \theta)$, $b_Q(\rho, \theta)$ and $\varphi_Q(\rho, \theta)$ represents the background, contrast and initial phase in the new (ρ, θ) coordinate system, respectively. In this way, a circular carrier interferogram is converted to a linear carrier interferogram. Rearranging the linear carrier interferograms using,

$$I'(N\rho + n, \theta) = I_{Qn}(\rho, \theta) \tag{5}$$

allows the rearranged Spatial-Temporal Fringe(STF) to be expressed by,

$$I'(\rho',\theta) = a_Q(\rho',\theta) + b_Q(\rho',\theta)\cos\left[2\pi f_c\rho' + \varphi_Q(\rho',\theta) + \varepsilon_Q(\rho',\theta)\right] \tag{6}$$

where

$$\varepsilon_Q(\rho',\theta) = \sum_{n=0}^{N-1}\sum_{m=-\infty}^{\infty} \varepsilon_{Qn}\delta(\rho' - Nm - n, \theta) \tag{7}$$