# Parallel two-step phase shifting interferometry using a double cyclic shear interferometer

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**Abstract:** A parallel two-step polarizing phase shifting interferometer based on a Double Cyclic Shear Interferometer (DCSI) is proposed in this paper for quantitative phase imaging. The system has the advantage of retrieving the derivative phase data map directly. Due to its configuration, it presents better stability against external configurations than other types of interferometers. The DCSI generates two π-shifted interferograms, which are recorded by the CCD camera in a single-shot. The separation between parallel interferograms can be varied in the two axes for convenience. To obtain the optical phase data map, a parallel phase shift between interferograms is obtained by rotating a half wave plate retarder. We analyzed the cases of four patterns with shifts of π/2 captured in two shots; the optical phase was processed by a four-step algorithm. Related experimental results obtained for microscopic transparent samples are presented.



OCIS codes: (050.5080) Phase shift; (070.6110) Spatial filtering; (110.0180) Microscopy; (120.3180) Interferometry; (120.5050) Phase measurement; (260.5430) Polarization.

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## 1. Introduction

Conventionally, in interferometric systems, the object and reference waves travel along separate paths, which affects each beam in a different form due to environmental disturbances; therefore, if proper precautions are not taken, the fringe pattern at the observation plane is unstable [1]. To solve this problem, cyclic path interferometers can be used, in which the waves are self-reference. The waves go along the same optical path, and in this way, the two beams are affected in the same manner by the same perturbation, which reduces the instabilities present. It has been extensively shown that the cyclic shear interferometer (CSI) presents stability against external vibrations, and also that it is capable of obtaining the directional derivative of the wavefront directly, this last by laterally or radially applying a shear, conveniently [1–3]; for that and more reasons, it presents several advantages in its implementation, mostly in retrieving the phase data map by means of interferometric methods. Phase shifting interferometric techniques are a powerful measuring tool, but their implementation sometimes turns out to be difficult when the facilities are not properly conditioned to get rid of external vibrations and impact directly in the phase data measurement, manufacturing inline productions for example. To eliminate some of these drawbacks, some authors have proposed several methods to obtain the optical phase using polarization techniques [4] and diffractive elements. Most implementations use two-stages [5–7], or show the capability of obtaining *n*-interferograms simultaneously [8–10]; some of these systems require diffractive elements such as phase grids or absorption gratings. The most used in the industry nowadays are pixelated phase mask interferometers, with one of the limitations of these systems being that the modulating phase-mask remains fixed, placed before the CCD light sensor [9]. In order to reduce the cost of operations, we present an alternative system that does not use diffractive elements, and still we can obtain the necessary phase shift used for the measurement. The system is based on obtaining replicas of the interferograms using the cyclic path configuration of the CSI, added with the capability of polarization phase shifting techniques [9,11]. We know from [11], N.I. Toto-Arellano et al, that a CSI can generate two beams with orthogonal polarizations. If these two beams go into a second CSI, we are capable of generating four beams, which can be properly made to interfere by displacing the mirror of this last CSI. As a result, we obtain the interference of pairs of beams, resulting in two interference patterns [12–15] that can be used to obtain the relative desired phase shift by using polarization phase shifting techniques. As shown in the following sections, the patterns generated by the Double Cyclic Shear Interferometer (DCSI) have relative phase shifts of $\pi$, and their separation can be freely adjusted. These results are convenient to reduce the number of phase steps used to process the optical phase information. The principal advantage of this system, compared with others previously published [6,7,12–15], is the elimination of the diffractive element and the polarizer array used at the output of the interferometer.

## 2. Experimental setup: double cyclic shear interferometer

The experimental setup of two step parallel phase-shifting interferometry is sketched in Fig. 1. As shown in the figure, the experimental set-up consists of two coupled cyclic shear interferometers, $CSI_0$ and $CSI_1$. In Fig. 1(a), representing the first cyclic shear interferometer ($CSI_0$), illumination comes from a polarized He-Ne laser, operating at λ = 633 *nm*; its polarization is arranged to be at 45° (by the system made up of a half-wave plate, $H_0$, and the linear polarizer, $P_0$). The polarizing beam splitter, $PBS_0$, splits the incident beam into perpendicular and parallel polarizing components, and their separation is controlled by the lateral movement ($\Delta x_0$) of the mirror $M_0$'. This configuration allows for two cases, depending on the separation obtained ($x_0$) and the beam transversal section ($a$): the first case, if $x_0 \geq a$, will result in two parallel beams with orthogonal polarization (with some considerations taken in the $CSI_1$, this will act as a quasi-common path interferometer); the second case, when $x_0 \leq a$, will result in a single sheargram. $CSI_1$ will be used to obtain replicas of the shearogram.

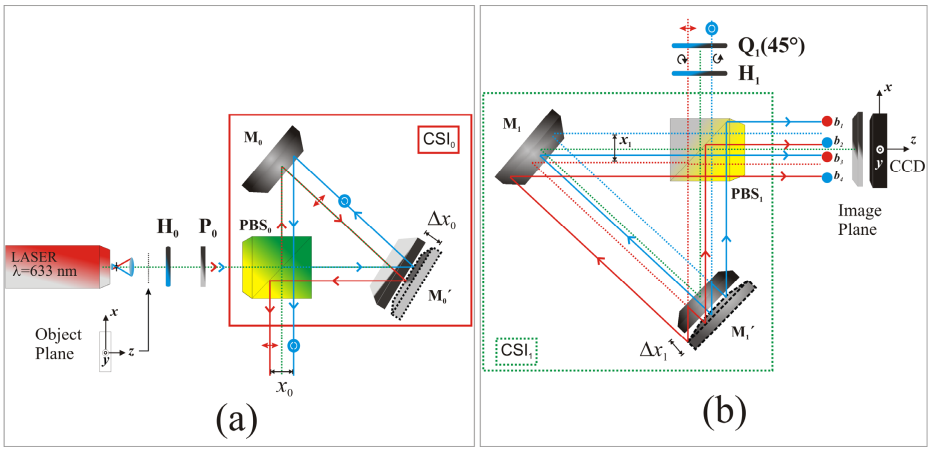


Fig. 1. Two step parallel phase-shifting interferometer (a) Optical setup scheme of the cyclic shear interferometer. (b) Coupled cyclic shear interferometer used to generate parallel interferograms. $Q_i$: Quarter wave plates. $H_i$: Half wave plates. M: Mirrors. $PBS_i$: Polarizing beam splitters. $\Delta x_i$: Adjustable mirrors. $x_i$: beam separation. $b_i$: Split beams.

At the output of the optical system, shown in Fig. 1(a), the first quarter-wave plate ($Q_1$) converts one of the two interfering beams into a right-handed circularly polarized beam and the second interfering beam into a left-handed circularly polarized beam [4]. The half-wave plate converts the right-handed state to left-handed, and the left-handed state to right-handed, and as the plate is rotated an angle χ, the phase difference between the test and reference beams changes by 4χ. The coupled $CSI_1$ splits the two beams generated by $CSI_0$, see Fig. 1(b), and yields four beams ($b_1$,$b_2$,$b_3$ and $b_4$) that can interfere properly, thereby allowing the generation of two interference patterns with a relative phase shift of π. In this case, it is not necessary to place a linear polarizer covering each one of interferogram [8], the use of the $PBS_1$ in the $CS_1$ achieves this function. This allows the use of less optical components reducing the associated error of them related with the polarizers and retarders angles [8,9]. In order to generate four interferograms in two shots with only one shift, the first step is obtain two sheared interferograms with a relative π shift at the output of the DCSI (The relative phase shift in this two interferograms are $I_1 = 0$ and $I_2 = 180°$) [10]; in the second step, we rotated the half wave plate ($H_1$) at angle of χ = 22.5°, by this procedure we obtain two new interferograms with a relative phase shift of π/2 ($I_3 = 90°$ and $I_4 = 270°$). As a result we could obtain the necessary four π/2 phase shifted interferograms in only one additional stage. We are able to obtain two applications: in the case when $x_0 \geq a$ and the object is placed on one of the beams obtained in $CSI_0$, the result is the phase of the incident wavefront; for the case when $x_0 \leq a$ and the object is placed at the entrance of the system, we are capable of obtaining the phase derivative of the wavefront directly. Since the first case is well known [4,8–11], for simplicity, the second case is considered (phase derivative); because of the derived, information can be extracted as the out of plane deformation field [16], then if $x_0 \leq a$, the overlapped beams are: $b_1 + b_2$ and $b_3 + b_4$ (See Fig. 2).

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In this case, the lateral displacement ($\Delta x_1$) of the mirror $M_1$' allows to control the four beams in *x*-*y* axis resulting in an adjustment of the $x_1$ positions of both parallel phase shifted interferograms at the output of the DCSI (Media 1). Media 1 shows the two possible operation modes of the system. The mode I allows to obtain the derivative of the phase because it behaves as a lateral shearing interferometer while in the mode II, the phase itself can be retrieved due of the two beam generation of the $CSI_0$ similar to a two-windows interferometer [8], nevertheless due of the polarization properties of each beam [11], a linear polarizer need to be placed covering both interferograms. Figure 2 shows some representative results generated by the proposed system. As we said before, four beams are generated by the DCSI, 2(a). In 2(b)-2(c) we present the interferograms obtained using a misaligned lens as a probe object to generated an aberrated wavefront. The two interference patterns present a relative phase shift of π between them [15].

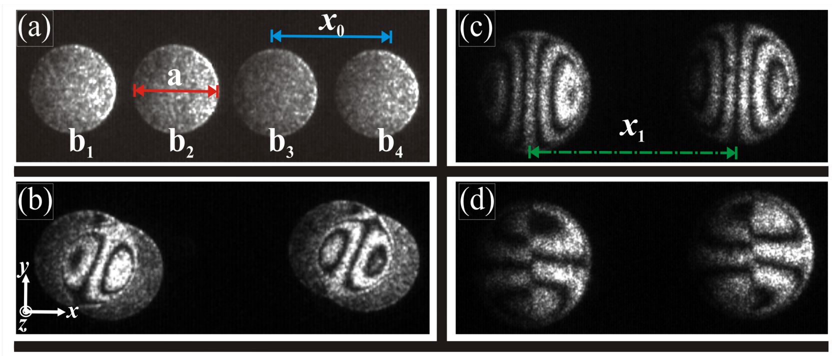


Fig. 2. Double Cyclic Shear Interferometer. (a) Four beams generated for the DCSI. (b) Interference patterns generated for the system with shear in the *x*-*y* direction. (c) Interference patterns generated for the system with shear in the *x*-direction. (d) Phase step: interference patterns generated for the system with shear in the *y*-direction. *a*: beam transversal section. $b_i$: Split beams. $x_0$: beam separation. $x_1$: Interferograms separation. (Media 1)

## 3. Two-step phase-shifting algorithm

Two interference patterns are captured by the CCD camera with a relative π phase shift between, represented as [3,8,9]

$$I_1(x,y) = A_0 + A_1 \cos\left[4\chi - \frac{\partial\phi(x,y)}{\partial x}\right] \quad , \quad I_2(x,y) = A_0 - A_1 \cos\left[4\chi - \frac{\partial\phi(x,y)}{\partial x}\right] \quad (1)$$

where χ represents the angle of the half wave plate $H_1(\chi)$ at the output of the $CS_0$, and it will be act as the phase shifter in the interference patterns. This shows that as the half-wave plate is rotated an angle χ, the phase difference between the reference and test beams changes by 4χ. The amplitude modulation terms remain constant in each step because we are not using diffractive elements to obtain the replicas [8,16]. As we said before, by rotating the half wave plate $H_1(\chi)$, with χ = 22.5°, another pair of interferograms will be obtained with a relative phase shift of 90° respect with the first capture, these can be represented as:

$$I_3(x,y) = A_0 + A_1 \sin\left[4\chi - \frac{\partial\phi(x,y)}{\partial x}\right] \quad , \quad I_4(x,y) = A_0 - A_1 \sin\left[4\chi - \frac{\partial\phi(x,y)}{\partial x}\right] \quad (2)$$

in order to implement the well-known four step algorithm to retrieve the phase data map [16]. This is calculated as

$$\frac{\partial\phi(x,y)}{\partial x} = \tan^{-1}\left[\frac{I_3(x,y) - I_4(x,y)}{I_1(x,y) - I_2(x,y)}\right] \quad (3)$$

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After removing the 2π ambiguity by means of a phase unwrapping process, the optical phase can be obtained. In order to remove the background phase, the phase retrieval procedure should include a phase reference in step where the background in measured beforehand [17,18]; the background phase is measured without the object target [18]. When operating the DCSI to obtain the lateral shearing interferometry, taking the shear direction in the object plane introduced along the *x*-directions, the phase distribution is related to partial slope $\partial w(x, y) / \partial x$ [19]:

$$\frac{\partial \phi(x, y)}{\partial x} = \frac{4\pi}{\lambda} \cdot \frac{\partial w(x, y)}{\partial x} x_0 \tag{4}$$

where $x_0$ is the lateral shear introduced.

## 4. Experimental results

For the experimental results presented, we used a 3.0 Megapixel CMOS sensor (color camera) with 2048 × 1536 pixels (pixel size, 3.2 x 3.2 μm). Each pattern was filtered using a conventional low-pass filter to remove sharp edges and details. One of the advantages of the system is that diffractive elements are not included to generate the two patterns. Due to this, it is not necessary to make corrections in fringe modulation. The CCD camera is adjusted to capture the images of two interference patterns simultaneously (in shot **I**, patterns $\boldsymbol{I}_1$ and $\boldsymbol{I}_2$ are captured). The fringe modulations of this interferogram pair are mutually complementary. Generating a parallel phase shifting for modulation of polarization, we get the other pair of interference patterns (in shot **II**, patterns $\boldsymbol{I}_3$ and $\boldsymbol{I}_4$ are captured). Figures 3-5 show the experimental results obtained. The experimental results for an acetate sheet with an average thickness of about 0.1 *mm,* and on which an arbitrary deformation in the *z* direction was caused, are shown below in Fig. 3, fringe pattern changes can be seen when a deformation is generated around a point on the acetate (enclosed in a circle). The figure shows the four patterns obtained in two shots, as well as the slope associated with the derivative of the phase. Figure 4 shows the experimental results obtained by depositing a layer of oil on a microscopy slide. The sample was subject to a mechanical load, and in this case, the deformation of the surface can be clearly seen in shearograms. Figure 4(a) shows the four patterns obtained in two shots, and 4(b) the slope associated with the derivative of the phase.

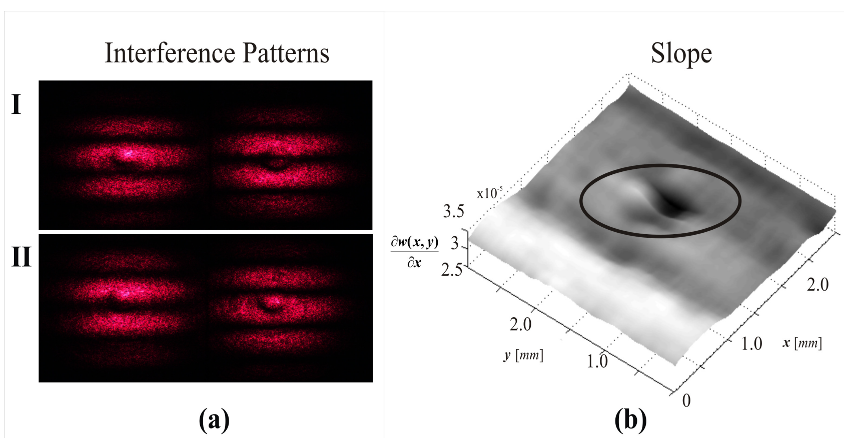


Fig. 3. Out of plane deformation generated by acetate. (a) Four shearograms generated for the DCSI. (b) 3D Slope in *y*-direction.

#198236 - $15.00 USD Received 30 Sep 2013; revised 22 Nov 2013; accepted 27 Nov 2013; published 17 Dec 2013
 

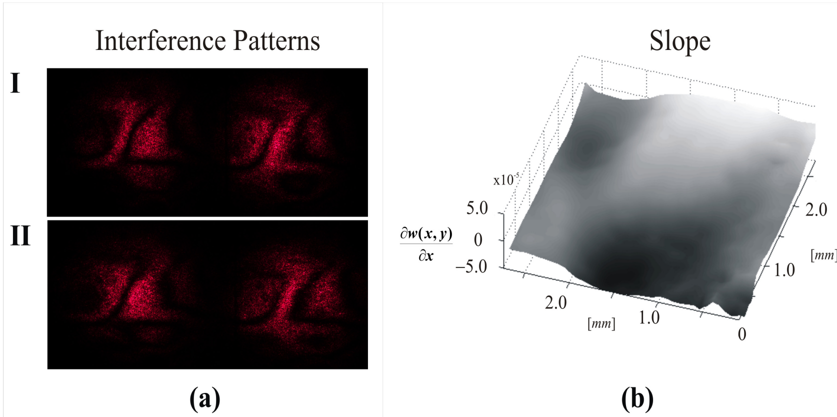


Fig. 4. Oil film on a microscopy slide (a) Four shearograms generated for the DCSI. (b) 3D Slope in *x*-direction.

The optical system can be modified to become a radial shear interferometer when a lens is placed on the trajectory of $CSI_0$, as a result, two images with slightly different in magnification will be focused at the CCD plane. For this case the phase change introduced due to out of plane deformation is given by [20]

$$\frac{\partial \phi(r)}{\partial r} = \frac{4\pi}{\lambda} \cdot \frac{\partial w(r)}{\partial r} r_0 \qquad (5)$$

Figure 5 shows the characteristic patterns of these symmetries combined with the deformation generated by a microscopic water bubble. Figure 5(a) shows the four shearograms obtained in two steps and Fig. 5(b) shows radial slope, the fringes obtained are contours of $r\left[\partial w(r)/\partial r\right]$, which clearly shows the deformation introduced by the water bubble (enclosed in a circle), see Fig. 5(c). The diameter of the object is approximately 0.5 *mm*.

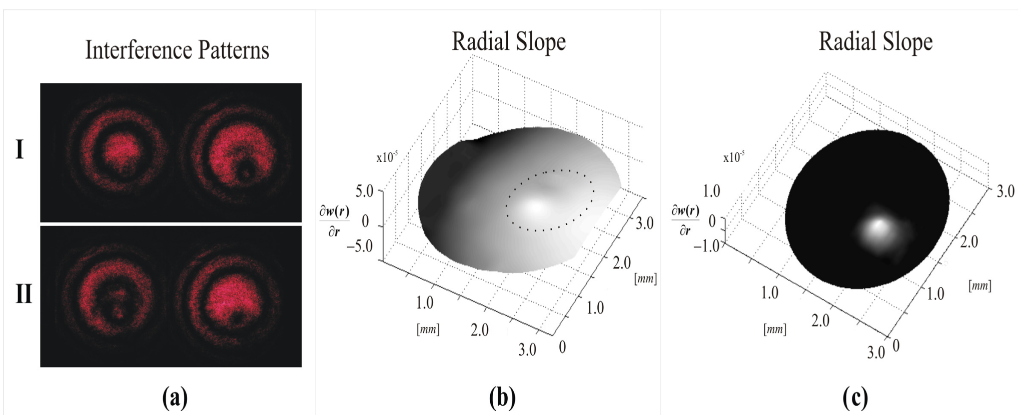


Fig. 5. Radial patterns combined with a water bubble of approximately 0.5 mm in radius. (a) Four shearograms generated for the DCIS. (b) Radial slope. (c) Deformation introduced by the water bubble.

## Final remarks

In this work, we propose a new configuration of shearing interferometry which is based on two coupled cyclic interferometers. Phase shifting is conducted through the polarization components. The technique presents the advantage of being free of non-linear shifting as

#198236 - $15.00 USD Received 30 Sep 2013; revised 22 Nov 2013; accepted 27 Nov 2013; published 17 Dec 2013

found in piezoelectric; another advantage is that the system is immune to vibrations because of the reference wavefront and object wavefront are common path, the shearing interferometer is to temperature and air and vibration insensitive, and due to the fact that diffractive elements (like gratings o micro polarizers) are not used in the optical system, errors due to the difference in amplitude or modulating, that generated the diffraction elements in the interference patterns seen in other systems are not present in the arrangement shown. The research provides a technique to optically obtain the first-order derivative of the phase wavefront of interferograms via parallel phase-shifting interferometry.

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