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Research Article

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Single shot interferometry using a two-interferogram phase shifting algorithm

Abstract: An interferometer capable of retrieving the phase information in a single shot was implemented, the system was made by taking into account the double interferogram output obtained in a Mach Zehnder interferometer and then retrieving the phase information using a two-step algorithm already encountered in the literature. By controlling the polarization properties of the system, a new polarization phase shifting technique was implemented based upon the rotation of two quarter wave retarders placed in each of the arms of the interferometer. We present the analytical model taking into account the necessary conditions presented by the demodulation method. The configuration presented does not require micro-polarizer arrays or diffraction gratings presenting the advantage of avoiding the use of conventional polarizing filters to control the phase shift. Experimental results are presented.

Keywords: interferometry; optical metrology; phase shifting; polarization.

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1 Introduction

Optical measurement techniques have become indispensable tools in many areas of science and engineering. The whole-field, non-contact and highly accurate measurements are among the principal features of these techniques. These techniques encode the sample information in the phase of a two-dimensional fringe pattern; several phase shifted replicas of this fringe pattern are used to retrieve information about the sample. Phase shifting techniques are often used in optical interferometry, digital holography [1], fringe projection profilometry [2], electronic speckle pattern interferometry and shearography [3]. The principal property is the capability of analyzing samples using non-contact techniques with high accuracy. The use of phase shifting modulated by polarization has the advantage of not requiring mechanical components, such as a piezoelectric transducer (PZT), to obtain the phase shifts. The main purpose of introducing polarization phase shifting techniques, added with replication systems, is to collect all the phase-shifted data in a single exposure in order to minimize time-varying environmental effects. Since the data are collected simultaneously, the effects of vibration and turbulence are greatly reduced and temporal data measurement can be done.

Recently, polarization phase shifting (PPS) techniques have acquired a wide usage in several sensing fields like holography [4], optical coherence tomography [5] and interferometry [6–8] due of its capability to be matched with single shot techniques by obtaining phase shifted replicas of the sensing object in a single capture. Several single shot techniques employing PPS techniques can be found in the literature: Using phase/amplitude gratings in a 4-f system [9]; using a four-channel polarization phase-stepper optics coupled to a wedge prism, or non-polarizing beam splitters, combined with wave plates and Wollaston prisms [10]. The industry standard today are pixelated phase mask interferometers [8, 11]. The most common PPS interferometry techniques are based on controlling the phase shift by rotating polarization components, such as linear polarizers or half-wave retarders placed at the output of the interferometer, whose reference and object beams have orthogonal linear polarization states [12, 13]. Studies have been done previously taking into account the usage of elements not

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centered on the wavelength of the laser source [14, 15] and also a thorough phase error analysis by the polarization and interferometric components [16]. In the implementation of the rotating polarizers (or half wave plates) problems arise when the interference beams do not have circular polarization states, mostly obtained by retardances changes. By this same approach the same analysis can be done by adding retardance parameters. Phase shifts occurred between the polarizing beam splitter cubes interfaces that were not taken into account nor the small errors in the polarization parameters of the components.

Research has been done in the phase demodulation algorithms employing two interferograms [17, 18] and more recently algorithms based on fringe analysis processing techniques [19–21] resulting in a good candidate to be employed in single shot interferometers. In order to correctly implement these algorithms, two conditions need to be taken into account for a successful implementation: 1) The relative phase shift between the interferograms needs to be different from π, and 2) the interferograms bias and amplitude modulations terms need to be similar. These conditions could be solved by employing polarization techniques and fringe pattern normalization algorithms [22, 23]. Two-interferograms phase demodulation systems using PPS techniques are already encountered in the literature; some of their principal properties are: using cyclic path configurations introducing a controllable phase shift by rotating half-wave plates or a polarizer [24, 25]. By using gratings and controlling the phase shift by placing a linear polarizer on each replica [26]. Our implemented system has two major properties: the first is the suppression of extra replication systems (gratings or pixelated phase mask cameras) by taking into account the two generation output obtained directly by the interferometer; the second property is the control of the phase shift by rotation of quarter wave plate (QWP) retarders and not by linear polarizers or half wave plates.

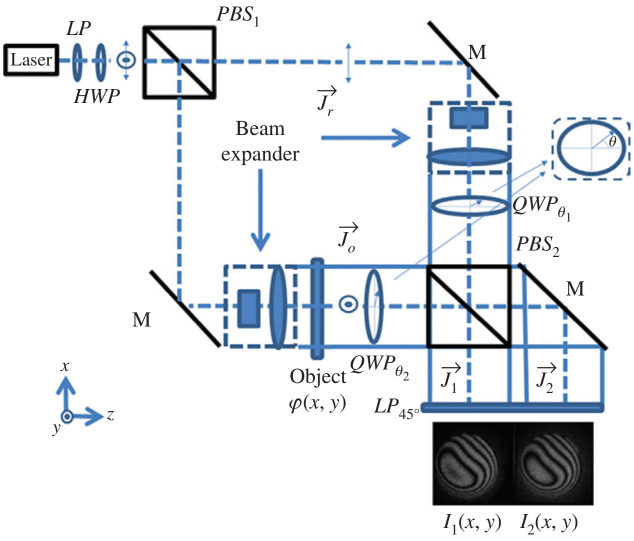

Figure 1 Polarizing Mach-Zehnder Interferometer used to obtain two-phase shifted with a relative phase shift different of π. *PBS*, Polarizing beam-splitter; *LP*, linear polarizer; *QWP*, quarter wave-plate; *M*, Mirror.

2 Polarization phase shifting principle by using quarter wave plates

Figure 1 presents the experimental setup based on a Polarization Mach-Zehnder Interferometer (PMZI), with the addition of two QWPs in a rotatory stage, one placed in each arm of the PMZI. A mirror is placed at the output of the PMZI to have the two phase shifted interferograms at the same image. By using the Jones calculation approach, a QWP_θ and a linear polarizer (P_ψ) at desired angle can be represented as [27]:

$$\mathrm{QWP}_\theta=\frac{1}{\sqrt{2}}\begin{pmatrix} 1+icos2\theta & isin2\theta \\ isin2\theta & 1\text{-}icos2\theta \end{pmatrix};\ \mathrm{P}_\psi=\begin{pmatrix} cos^2\psi & sin\psi cos\psi \\ sin\theta cos\psi & sin^2\psi \end{pmatrix}. \tag{1}$$

Following the polarization states of each beam, passing through each polarization component of the PMZI, the output polarization states can be obtained as

$$\begin{aligned} \vec{J}_1&=\mathrm{P}_{45}\cdot(\mathrm{P}_0\cdot\mathrm{QWP}_{\theta_1}\cdot\vec{J}_r+\mathrm{P}_{90}\cdot\mathrm{QWP}_{\theta_2}\cdot\vec{J}_0),\\ \vec{J}_2&=\mathrm{P}_{45}\cdot(\mathrm{P}_{90}\cdot\mathrm{QWP}_{\theta_1}\cdot\vec{J}_r+\mathrm{P}_0\cdot\mathrm{QWP}_{\theta_2}\cdot\vec{J}_0); \end{aligned} \tag{2}$$

taking the reference and object beams as $\vec{J}_r=\begin{pmatrix}1\\0\end{pmatrix}$ and $\vec{J}_0=\begin{pmatrix}0\\1\end{pmatrix}e^{i\varphi(x,y)}$ where $\varphi(x, y)$ is the phase information of the transparent sample. The sample is treated as a pure phase sample with no polarization properties. After making the corresponding matrix multiplication and obtaining its output intensity, the interferogram equation dependant of the angle (θ_1, θ_2) can be obtained as:

$$I_{1,2}(x,y)=A_{1,2}(\theta_1,\theta_2)+B_{1,2}(\theta_1,\theta_2)\sin[\varphi(x,y)+C_{1,2}(\theta_1,\theta_2)], \tag{3a}$$

$$\begin{aligned} A_1(\theta_1,\theta_2)&=\frac{1}{4}[3+cos(2\theta_1+2\theta_2)cos(2\theta_1\text{-}2\theta_2)],\\ A_2(\theta_1,\theta_2)&=\frac{1}{4}[1\text{-}cos(2\theta_1+2\theta_2)cos(2\theta_1\text{-}2\theta_2)], \end{aligned} \tag{3b}$$

$$B_1(\theta_1,\theta_2)=\frac{1}{4}[9+6\cos(2\theta_1+2\theta_2)\cos(2\theta_1-2\theta_2)+\cos(4\theta_1)\cos(4\theta_2)]^{\frac{1}{2}},$$
$$B_2(\theta_1,\theta_2)=\frac{1}{2}\sin(2\theta_1)\sin(2\theta_2), \tag{3c}$$

$$C_1(\theta_1,\theta_2)=\mathrm{atan2}(1-\cos(2\theta_1)\cos(2\theta_2),\ 2\cos(\theta_2+\theta_1)\cos(\theta_2-\theta_1)),$$
$$C_2(\theta_1,\theta_2)=\frac{\pi}{2}. \tag{3d}$$

These equations represents the bias, $A_{1,\,2}(\theta_1,\ \theta_2)$, amplitude, $B_{1,\,2}(\theta_1,\ \theta_2)$, and phase, $C_{1,\,2}(\theta_1,\ \theta_2)$ dependent variations of the quarter wave plates angles $(\theta_1,\ \theta_2)$, of the quarter wave plates. The purpose of having this approach is to obtain the permitted QWP angles where the two interferograms can be used for phase demodulation. By analyzing $I_2(x,y)$ terms it can be noted that there will not be any phase change due of the rotation of the QWP but the amplitude, $B_2(\theta_1,\ \theta_2)$, and bias, $A_2(\theta_1,\ \theta_2)$, terms will be varying with a dependance twice the angle of the variations of the QWP rotation. $I_1(x,\ y)$ will be used to control the relative phase shift between the interferograms. The final objective is to obtain at the output two interferograms with almost identical bias ($A_1(x,\ y) \approx A_2(x,\ y)$) and amplitude modulation terms ($B_1(x,\ y) \approx B_2(x,\ y)$).

Taking θ_1 and θ_2 as the angle of rotation of the QWP$_{\theta_1,\ \theta_2}$, located in the reference and object arm of the MZI, respectively, we are able to obtain both interferograms with a controllable relative phase shift by obtaining the bias, $A_{1,2}(\theta_1,\ \theta_2)$, and amplitude modulation, $B_{1,\,2}(\theta_1,\ \theta_2)$, terms dependent of the angle of the QWP$_{\theta_1,\ \theta_2}$. The relative variation of each interferogram can be represented in a 3D space where the $[x,\ y]$ axis represents the angular value, $[\theta_1,\ \theta_2]$, and the z axis present the change between each term (Bias, amplitude and Phase shift term). Figure 2 presents the difference for each term.

With the diagram of the relative change of each term, Figure 2A and B, we are able to obtain the regions were the bias and amplitude modulation term are almost equal, dotted regions in Figure 2C. Figure 3 shows the obtained phase shift dependent of the angles of the quarter wave plates. Experimentally speaking, by having choosing this angles both interferograms can be detected and they could be used with the phase demodulation algorithm, i.e., if θ_1=0° and θ_2=0° only one interferogram can be detected, on the other hand if we select θ_1=-50° and θ_2=-50°, two interferograms, with a relative phase shift of 21.2°, will be retrieved.

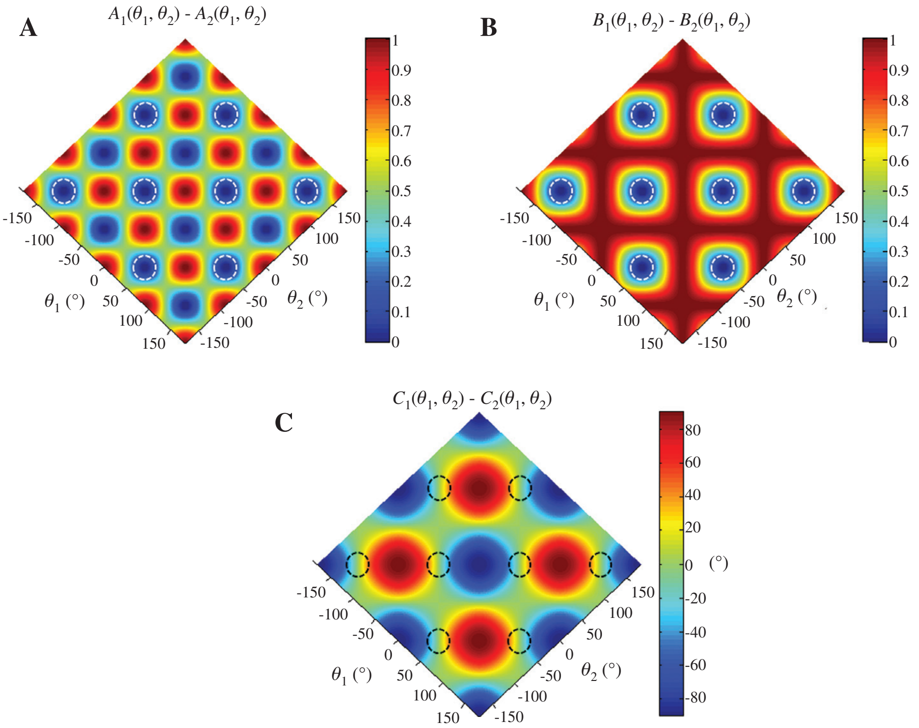

Figure 2 Relative difference of the interferograms terms dependent of the QWP rotations angles.
(A) Bias term, (B) Amplitude Modulation term and the (C) Phase Shift with the region where the amplitude and modulation terms are almost equal (dotted circles).

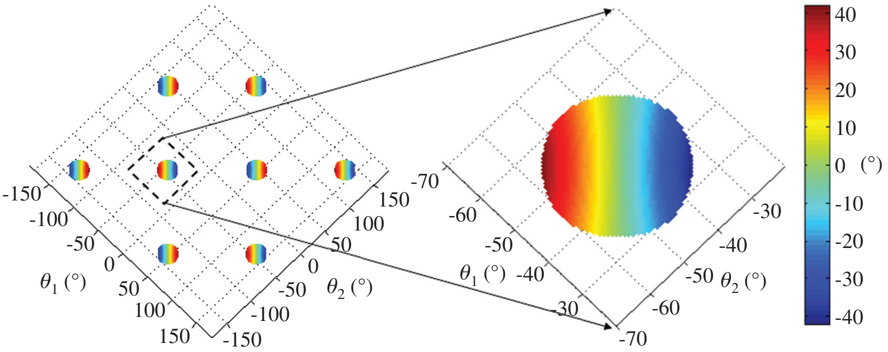

Figure 3 Permitted angles of the quarter wave plates where the amplitude and bias terms of both interferograms remain equal and can be used to retrieve the phase using the two step algorithm.

3 Experimental results

A He-Ne laser is utilized with a power of 20 mW and λ=0.633 μm allowing sufficient illumination intensity to carry out the experiment. The monochromatic camera used is based on a CMOS sensor with 1280×1024 pixels and with a pixel pitch of 6.7 μm. Assumptions were taken that errors in the diattenuation or retardance parameters are not encountered in the optical components. A more formal analysis by using these parameters is currently being studied by the authors. As the phase shifting technique relies on taking ideal polarization components, we were limited by the aperture size of the quartz retarders and they were placed before the beam expanders; in this case the clear aperture size was sufficient because we were only dedicated to show phase changes occurred by lens misalignments. The same phase shifting property could be obtained by using only one beam expander at the entrance of the interferometer. An iris aperture was used to find a common zone between the interferograms by a centroid calculation, the interferograms can be selected and used for the phase demodulation process [15]. Figure 4 presents experimental results corresponding to misalignments of one of the beam expanders of the object beam.

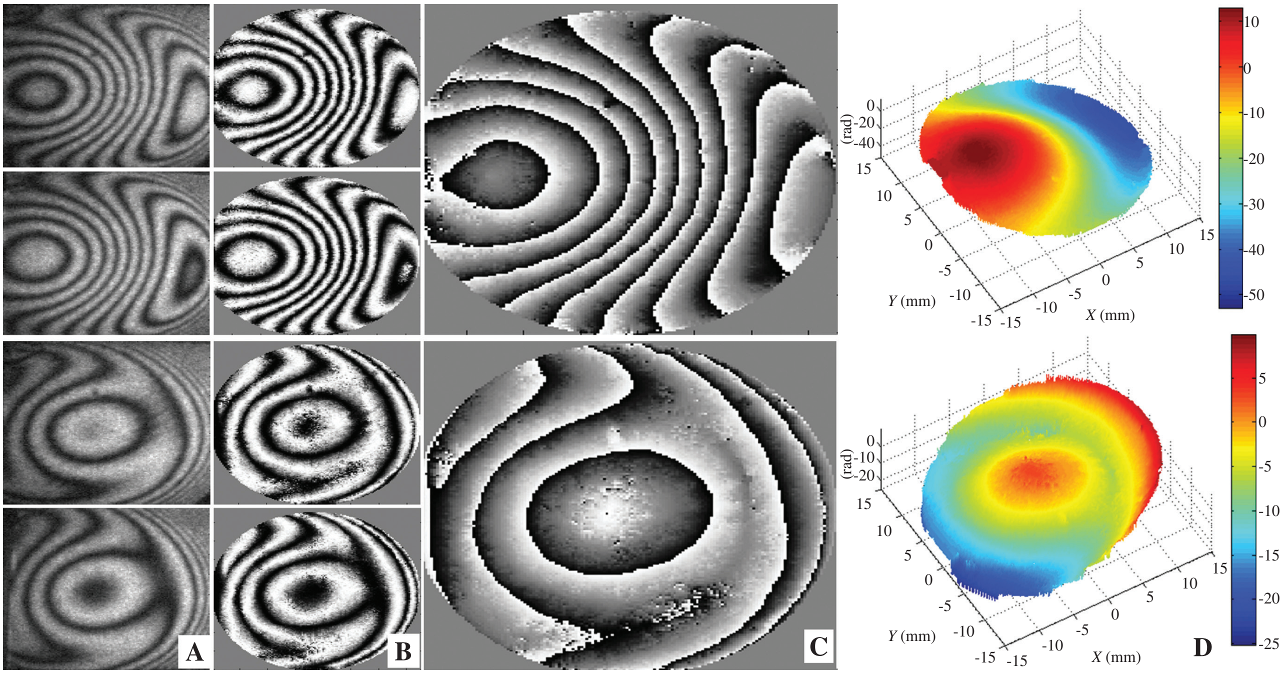

Figure 4 Experimental results obtained by misalignment one of the collimating lens in the beam expander at the object beam. (A) and (B) Interferograms retrieved, (C) wrapped and (D) unwrapped phase.

The two interferograms are captured in a single image by the CCD camera and processed by a fringe pattern normalization algorithm [22]. The phase demodulation term is retrieved by a two-step demodulation algorithm [20]. To unwrap the phase map, the 2D Goldstein branch cut algorithm is used [28].

4 Conclusions

We presented a single shot interferometer based on polarization phase shifting techniques. The major novelty of the present system is to avoid the use of special components to replicate the beams such as pixelated phase mask or amplitude/phase gratings. The system takes into account the double output encountered in the Mach-Zehnder interferometer by using polarization phase shifting techniques based on changing the rotations of quarter wave plates retarders. The system is considerably more simple than previous proposals, showing a suitable alternative to implement in an industrial environment.

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