Optics and Lasers in Engineering 58 (2014) 33–38

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

One-shot phase-visibility modulating interferometry by on–off non-quadrature amplitude modulation

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ARTICLE INFO

Article history:
Received 9 September 2013
Received in revised form
1 January 2014
Accepted 2 January 2014
Available online 10 February 2014

Keywords:
Interferometry
Phase retrieval
On–off amplitude modulation

ABSTRACT

This manuscript presents a proposal for achieving in a single-shot the phase-visibility modulating interferometry method. The setup is based on a 4f optical system consisting of three apertures at the input plane and a grid with a fill factor of 1/2 at the Fourier plane. One of the apertures serves as a probe beam and the other two apertures serve as reference beams, with which a reference beam modulated in phase and amplitude by the on–off non-quadrature amplitude modulation method is created. We show that the grid implements simultaneously the on–off non-quadrature amplitude modulation technique; therefore multiple interferograms can be obtained in a single-shot. A theoretical model will be shown supported by the experimental results.

1. Introduction

Recently, a novel approach for implementing the phase-shifting interferometry (PSI) technique was theoretically proposed [6,7]. This is achieved without the use of any known method such as changing the optical-path [1], modulation of polarization [2], grating displacement [3], Doppler [4], or Zeeman [5] effects, among others. The proposed approach involves modulating only the phase (PM) of a reference beam, which was achieved by the quadrature [6] or non-quadrature [7] amplitude modulation method (QAM and NQAM, respectively). As known [6,7], NQAM adds two reference beams out of phase by a value other than 0 or π, while QAM adds two beams out of phase by $\pi/2$. In general by the amplitude-only modulation of these two reference beams, NQAM obtains a beam modulated in phase and amplitude (PAM), although PM or amplitude modulation (AM) also is possible. For an experimental implementation of NQAM in PM, AM, and PAM modes, two amplitude filters (AFs) with a good quality characterized exhaustively are needed so that they do not introduce undesired phases.

Thus, the experimental implementation of PSI by QAM or NQAM could be a difficult task. However a very special case that can avoid these requirements occurs when the AF is operated in on–off mode, which is equivalent to unblock–block the path of the beam. This makes the use of AF (such as neutral density filters, NDFs) unnecessary since only a dark-sheet for each beam can be used, as it was shown in our recent report [8]. In that paper the spatial PAM by on–off NQAM in two beams of a three-beam Mach–Zehnder interferometer (MZI) was achieved forming with this an equivalent reference beam while the third beam was considered as the probe, which resulted in each interferogram having inhomogeneous phase and visibility variations. Despite that, the phase retrieval was obtained with six-camera frames in an analytic form. This method was named phase-visibility modulating interferometry (PVMI). However, because MZI is susceptible to mechanical vibrations, atmospheric turbulence, or temperature gradients, in this type of implementation one of the major sources of error is the temporal variation of the phase difference between the two references with which the on–off NQAM method was implemented. In this manuscript, to avoid the drawbacks mentioned before, an experimental setup for implementing PVMI by on–off NQAM in a single frame of a CCD camera is proposed.

2. Theoretical model

The proposed setup is based on a 4f optical image system employing two transforming lenses L_1 and L_2 with focal distance f. It contains three apertures at the object plane, where two apertures are used for achieving NQAM to obtain a reference beam in PAM mode while the third aperture is used as a probe beam. A grid formed by two crossed Ronchi rulings of spatial period u_p and fill factor of 1/2 in both perpendicular directions is used as a filter at the Fourier plane, as shown in Fig. 1. This setup is referred to as a triple-aperture common-path interferometer (TACPI). It has a high mechanical stability because the beams travel through the same optical components. Thus, the phase variations in the beams are compensated, so that the main

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http://dx.doi.org/10.1016/j.optlaseng.2014.01.007

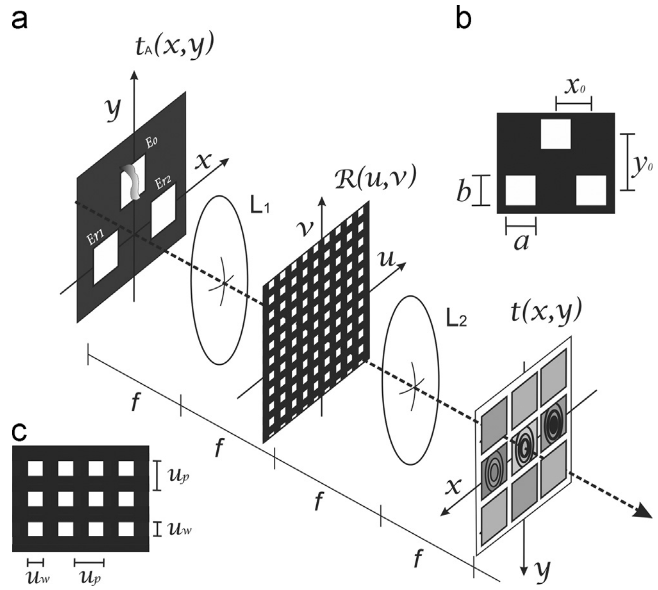

Fig. 1. Scheme of a TACPI for achieving the PVMI method in a single shot by the on–off NQAM carried out by the grid.

disadvantages cited in [8] are strongly reduced. Another important advantage of the present proposal is that the grating placed in the Fourier plane intrinsically generates the amplitude modulation of the reference beams without using any kind of AF, such as an NDF or a dark-sheet and also without any mechanical movement of an optical element or modulation of polarization with any kind of fine calibration. Besides, due to the special case of the fill factor chosen (1/2), the on–off NQAM method is successfully achieved. Additionally, because several diffraction orders are simultaneously observed at the image plane, nine frames can be captured in a single shot, from which three different combinations of six frames could be chosen for phase extraction. This feature makes this proposal capable of measuring the phase of a dynamic object in real time. In this aspect, it is very well known that many methods in PSI have been proposed and very well justified theoretically and experimentally, but all of them need additional optical elements such as micro-polarizers placed at each pixel of a CCD camera [9], or they need to generate right and left circular or quasi-circular polarization at the input plane and several polarizers at the image plane in a double-aperture common-path interferometer (DACPI) [10] with a Ronchi ruling [11] or a phase grating [12] as spatial filters; or to place a beamsplitter cube at the image plane instead of polarizers for phase-shifting [13,14]. In summary, the present proposal could be easily implemented in an experimental setup and with more accuracy than the others aforementioned.

Because of the far field Fraunhofer diffraction effects, every aperture in Fig. 1 will be replicated at the image plane by a distance $\lambda f/u_p$ in both directions, where λ is the wavelength of the laser source. To produce the overlapping of the diffraction orders the distance between the centers of each window (x_0 on x-direction and y_0 on y-direction) must be a multiple integer of $\lambda f/u_p$ [12], so for this case $x_0 = y_0/2 = \lambda f/u_p$ are assumed. Therefore if a non-tilted, monochromatic, coherent, and linearly polarized plane wave is used to illumine this setup, the optical field leaving these windows can be described as

$$t_A(x,y) = w(x+x_0,y)E_{r1} + w(x,y-y_0)E_0 + w(x-x_0,y)E_{r2}, \tag{1}$$

which represents the transmittance function at the object plane, where the coordinates for $E_s = A_s e^{i\phi_s}$ (with $s = r1, r2, o$) have been omitted. A_s and ϕ_s represent the amplitude and phase of the references and probe beam, respectively. $w(x,y) = \mathrm{rect}(x/a_w)\mathrm{rect}(y/b_w)$ is the window function of sides a_w and b_w, with $\mathrm{rect}(\cdots)$ denoting a rectangle function. Then, the output field at the image plane is expressed as

$$t(x,y) = t_A(x,y) \otimes \otimes R(x,y), \tag{2}$$

where $R(x,y)$ is the impulse response of the binary grid given by

$$R(x,y) = \sum_{m,n} c^c_{m,n}\delta(x-mx_0, y-nx_0), \tag{3a}$$

the complex coefficient $c^c_{m,n}$ is given by

$$c^c_{m,n} = c_{m,n}e^{-i(m\alpha_d + n\beta_d)}, \tag{3b}$$

where

$$c_{m,n} = \frac{1}{4}\mathrm{sinc}\left(\frac{m}{2}\right)\mathrm{sinc}\left(\frac{n}{2}\right);\ \alpha_d = 2\pi\frac{u_d}{u_p};\ \beta_d = 2\pi\frac{v_d}{u_p} \tag{3c}$$

with u_d and v_d representing a displacement with respect to the optical axis measured from the center of a bright bar in the grid; then, the resulting output transmittance is

$$t(x,y) = \sum_{m,n} c^c_{m,n} t_A(x-mx_0, y-nx_0), \tag{4}$$

which is a replica of the input field in all space separated by x_0 and modulated by $c^c_{m,n}$. By substituting Eq. (1) into (4) it can be obtained that

$$\begin{aligned} t(x,y) = \sum_{m,n} c^c_{m,n}[&w(x-(m-1)x_0, y-nx_0)E_{r1} \\ &+ w(x-mx_0, y-(n+2)x_0)E_o \\ &+ w(x-(m+1)x_0, y-nx_0)E_{r2}]. \end{aligned} \tag{5}$$

Alternatively, Eq. (5) can be rewritten as

$$t(x,y) = \sum_{m,n} w_{m,n}(x,y)(c^c_{m+1,n}E_{r1} + c^c_{m,n-2}E_o + c^c_{m-1,n}E_{r2}), \tag{6}$$

which indicates that, in each replicated window denoted by $w_{m,n}(x,y) = w(x-mx_0, y-nx_0)$, the three entrance fields are superposed, but with their amplitudes modulated by the complex coefficients of the ruling, adding a phase-step and attenuating the amplitudes in a discrete form obeying the sinc function according to the m,n-th diffraction order. The irradiance observed by a detector in the window $w_{m,n}$ is given by

$$I_{m,n} = A^2_{m,nr} + c^2_{m,n-2}A^2_o + 2c_{m,n-2}A_{m,nr}A_o\ \cos(\phi - \Delta\phi_{m,nr}), \tag{7}$$

where the object phase is defined as $\phi = \phi_o - \phi_{r1} + \alpha_d + 2\beta_d$. It can be demonstrated that the resulting reference amplitude and the additional phases are given by

$$A^2_{m,nr} = c^2_{m+1,n}A^2_{r1} + c^2_{m-1,n}A^2_{r2} + 2c_{m+1,n}c_{m-1,n}A_{r1}A_{r2}\ \cos\ \Delta\phi_T, \tag{8a}$$

$$\tan\ \Delta\phi_{m,nr} = \frac{c_{m-1,n}A_{r2}\ \sin\ \Delta\phi_T}{c_{m+1,n}A_{r1} + c_{m-1,n}A_{r2}\ \cos\ \Delta\phi_T}, \tag{8b}$$

and the visibility can be expressed as

$$V_{m,n} = \frac{2c_{m,n-2}A_{m,nr}A_o}{A^2_{m,nr} + c^2_{m,n-2}A^2_o}, \tag{8c}$$

where $\Delta\phi_T = \Delta\phi_{21} + 2\alpha_d$ is the total phase difference between the reference beams, and $\Delta\phi_{21} = \phi_{r2} - \phi_{r1}$ is the phase difference due to their optical path difference. $\Delta\phi_{m,nr}$ is an additional phase that depends on the amplitudes and phases of the reference fields, but because $\Delta\phi_T$ remains constant, $\Delta\phi_{m,nr}$ depends only on the amplitudes. If $\Delta\phi_T = 0,\pi$ then no PM is possible (see Eq. (8b)), only AM (see Eq. (8a)). But if $\Delta\phi_T \neq 0,\pi$, the PM, AM or PAM can indeed be achieved [15]. Therefore, the NQAM is implemented by the coefficients $c^c_{m,n}$, making the use of the amplitude filters unnecessary. For the gratings used, there are two relevant properties: for every non-zero even m or n, $c^c_{m,n} = 0$, and for every odd m or n, $c^c_{m,n} \neq 0$. As a consequence, $c^c_{m,n}$ only takes discrete values, and therefore the on–off NQAM version in PAM mode is