Optics and Lasers in Engineering 91 (2017) 144–150

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Characterization of axially tilted fibres utilizing a single-shot interference pattern

T.Z.N. Sokkar[a], K.A. El – Farahaty[a,*], M.A. El – Bakary[a], E.Z. Omar[a], M. Agour[b,c]

[a] Physics Department, Faculty of Science, Mansoura University, Mansoura, Egypt
[b] Physics Department, Faculty of Science, Aswan University, Aswan, Egypt
[c] BIAS-Bremer Institut für angewandte Strahltechnik, Klagenfurter, Bremen, Germany

ARTICLE INFO

Keywords:
Fibre characterization
Digital holography

ABSTRACT

We proposed a method to solve the problem of extracting meaningful phase information for a single-shot interference pattern taken for an axially tilted fibre sample. Conventionally such interference patterns can be not evaluated with appropriate accuracy. Here, such an interference pattern is considered to be a special hologram since it contains information about light propagated through a laterally fixed sample located at different axial planes. Thus, part of the test object in such a hologram is in focus and the other parts are out of focus. The proposed method can be considered as two complementary steps. In the first step the complex amplitude across the hologram plane is recovered using an adaptive spatial carrier frequency method. This is followed by the second step where the complex amplitude is numerically propagated within a given volume. Thus, planes where the test object is in focus are defined. Consequently, the phase distributions corresponding to all of these planes are together stitched. Thus a complete focus phase map for the fiber sample under test is obtained. From the obtained phase map the two dimensions refractive and the two dimensions birefringence of isotactic polypropylene fibre were calculated.

1. Introduction

In fibre science, the measurement of fibre's optical properties using optical techniques has become an indispensable step utilized to characterize the structure of these fibres [1–3]. The accuracy of the measurements is mainly depended on the technique which is used to measure the optical path difference (OPD) of light passing through a test fibre sample. From the OPD, optical properties of fibres such as the birefringence and the refractive indices can be determined.

When a light beam is incident on a fibre, its propagation relies on the nature of the fibre's material and thus the OPD of the output beam is varied. The change of the OPD usually is encoded within the phase information of light propagating through the fibre. Unfortunately, phase cannot be directly measured [4]. Using interference based methods such as two-beam [5] and multiple-beam Fizeau interferometry [6], the phase can be encoded in the intensity of the interference pattern. The intensity of the interference pattern can be gained for post processing using CCD camera sensors. Using an appreciate method, such as spatial carrier frequency [7–9] or temporal phase shifting methods [8,10], the phase information can be retrieved.

Here it is planned to use a method which is based on the spatial carrier frequency, since it requires only a single recorded interference pattern compared with the temporal phase sifting techniques. The adaptive spatial carrier frequency technique proposed in Ref. [4] is considered as an accurate method to retrieve the phase distribution of the tested fibre from the recorded interference pattern. The main idea of this technique can be summarized as follow. A fast Fourier transform is applied to convert the spatial domain of the interference pattern to frequency domain. Then an adapted band pass filter is applied to eliminate the unwanted spectral peaks. Consequently, an inverse Fourier transform is applied to the rest spectrum peak, thus the complex amplitude across the recording plane is obtained. Since this technique requires only a single interference pattern to extract the phase distribution, it is recommended to be used for characterizing and studying dynamic objects.

The single interference pattern can be obtained from standard interferometers including a Mach Zehnder interferometer [5], a Pluta polarizing interference microscope [11] and a Michelson interferometer [5]. All of these interferometric systems are based on coherent superposition of two beams, emitted from a light source but propagating in two different paths, at the recording plane where a digital recording medium like CCD camera is located [12]. In all of these techniques, the

* Corresponding author.
E-mail address: emam88@mans.edu.eg (K.A. El – Farahaty).

http://dx.doi.org/10.1016/j.optlaseng.2016.11.018
Received 12 June 2016; Received in revised form 5 November 2016; Accepted 18 November 2016
Available online 21 December 2016
0143-8166/

manual focusing is considered as a serious problem since it has a bad effect on the accuracy of the phase measurements [13,14].

Within the state of the art, the manual focusing problem was overcome using techniques based on digital holography [10,15] or computational shear interferometry CoSI [16]. Accordingly, the optical and structural properties of different fibres were measured with high degree of accuracy. It is worth to mention that the numerical reconstruction process for a digital hologram can be carried out by different algorithms such as convolution and Fresnel approaches [17].

For on-line characterization of fiber, there is no time left to align the fibre sample under test to be in all captured frames in focus. Consequently, the captured interference patterns are taken for an axially tilted sample. Accordingly, in the same captured frame parts of the test object are in focus and the other parts are out of focus. Here, these interference patterns are considered to be special holograms since it contains information about light propagated through the whole sample. Thus, part of the recorded interference pattern is treated as a standard interferogram. While the other out of focus parts are treated as a hologram.

Here we proposed a method to solve the problem of extracting meaningful phase information for these frames. The method can be considered as two complementary steps. In the first step the complex amplitude across the hologram plane is recovered using an adaptive spatial carrier frequency method. This is followed by the second step where the complex amplitude is numerically propagated with a given volume. Thus, planes where the test object is in focus are defined. Consequently, the phase distributions corresponding to all of these planes are stitched together. Thus, a phase map analog to the one obtained for an in focus fiber sample is obtained. The method is verified experimentally by measuring optical properties of isotactic polypropylene fibres using a system based on Mach-Zehnder interferometer. The 2D refractive indices in parallel and perpendicular direction and the 2D birefringence for the axially tilted interferogram of isotactic polypropylene fibre are calculated with relativity high accuracy.

2. Theoretical considerations

Digital holography is considered as one of the most effective techniques to investigate the optical wavefield of an axially titled sample [18,19]. The major advantage of this technique is the numerical reconstruction that enables to detect the best focus position for the tested sample [18–21]. Generally, the majority of the autofocusing approaches were worked under assumption that the image plane is parallel to the plane of the hologram acquisition [22]. Now, the numerical reconstruction of an axially titled sample via the digital holography becomes major step in many applications. These applications include tomography [23], velocity measurements, the extended focused image (EFI) [18] and 3D visualization [24]. Also, it is used to solved the Abbe diffraction problems for measuring the topography of micro-lenes that have numerical aperture higher than that an applied imaging system [22]. Although important of investigation the optical wavefield of an axially titled sample, a few approaches for refocusing between two mutually titled planes in single image have been proposed.

Generally, a digital hologram is generated by coherent superposition of a reference and an object wave fields having the phase φ_R and φ_O, respectively. Both wave fields are linearly polarized in the same direction. Assume that the reference A_R and the object A_O wave fields can be described, respectively, by the following equation [7]:

$$A_R(\vec{x})=|A_R(\vec{x})|.\ \exp[i\varphi_R(\vec{x})],\ A_O(\vec{x})=|A_O(\vec{x})|.\ \exp[i\varphi_O(\vec{x})] \tag{1}$$

where, the vector $(\vec{x})=(x_m, \quad x_n)$ represents a vector across camera plane. The superposition of the two wave fields $A(\vec{x})$ is expressed by the complex sum:

$$A(\vec{x})=A_R(\vec{x}) + A_O(\vec{x}) \tag{2}$$

Consequently, the intensity of the interference pattern can be written as:

$$I(\vec{x})=|A(\vec{x})|^2=C(\vec{x}) + A_O^*(\vec{x}).\quad A_R(\vec{x})+A_O(\vec{x}).\ A_R^*(\vec{x}) \tag{3}$$

here * refers to the complex conjugation and $C(\vec{x})$ represents the incoherent term which is given by:

$$C(\vec{x}) = |A_R(\vec{x})|^2+|A_O(\vec{x})|^2 \tag{4}$$

2.1. Numerical focusing of object wave field

One of the main features of digital holographic microscopy (DHM) is the extended depth of focus of standard microscopes [18] by means of numerical propagation. Thus imaging through several focus planes from only one recoded hologram can be realized [21]. To do this, recovering of the complex amplitude, i.e. the phase and amplitude, from the hologram is required. The recovering process will be discussed in the following.

For extracting the phase information of an interference pattern represented by Eq. (3), the adaptive spatial carrier frequency approach was used. This approach requires the modulation of the interference pattern with a spatial carrier frequency$\vec{f}_o$. Accordingly, the intensity of the interference pattern can be rewritten as:

$$I'(\vec{x})=C(\vec{x})+A_O^*(\vec{x}).\quad A_R(\vec{x}).\ Q^*(\vec{x})+A_O(\vec{x}).\ A_R^*(\vec{x}).Q(\vec{x}) \tag{5}$$

where $Q(\vec{x})$ represents the modulation by the following linear phase term:

$$Q(\vec{x})=\exp(i2\pi f_0\vec{x}) \tag{6}$$

It is noted that $\vec{f}_o$ is utilized to separate the three terms of Eq. (5) across the Fourier domain. Thus, applying the Fourier transform on Eq. (5) with taking the shift theorem of the Fourier transform into account, one can write the result in Fourier domain as:

$$\hat{I}'(\vec{f})=\hat{C}(\vec{f})+\mathcal{I}\{A_O^*(\vec{x}).\quad A_R(\vec{x})\}(\vec{f})\otimes\delta(\vec{f}-\vec{f}_o) + \mathcal{I}\{A_O(\vec{x}).\ A_R^*(\vec{x})\}(\vec{f})\otimes \delta(\vec{f}+\vec{f}_o) \tag{7}$$

here the hat and $\mathcal{I}$ refer to the Fourier transform, the vector $\vec{f}=(f_m, \quad f_n)$ represents a vector at the frequency domain, $\otimes$ denotes the convolution and δ refers to the Dirac-delta function [16]. In order to filter out the first and the second terms of Eq. (7), adapted band pass filter has been performed. Then, shifting the third term back to the centre of the frequency coordinates. Thus, Eq. (7) can be rewritten as:

$$\hat{I}'(\vec{f})=\mathcal{I}\{A_O(\vec{x}).\ A_R^*(\vec{x})\}(\vec{f}) \tag{8}$$

The complex amplitude across the recording plane $A(\vec{x})$ can be obtained, by taking the inverse Fourier transform of Eq. (8) as shown in the following equation:

$$A(\vec{x})=\mathcal{I}^{-1}\{\hat{I}'(\vec{f})\}(\vec{x})=[A_O(\vec{x}).\ A_R^*(\vec{x})](\vec{x}) \tag{9}$$

Therefore, the interference phase difference $\Delta\varphi = \quad \varphi_O-\varphi_R$ of the wave field can be calculated by:

$$\Delta\varphi(\vec{x})=\arctan\left[\frac{\mathrm{Im}(A(\vec{x}))}{\mathrm{Re}(A(\vec{x}))}\right], \tag{10}$$

where, $Im(A(\vec{x}))$ and $Re(A(\vec{x}))$ are the imaginary and real parts of $A(\vec{x})$, respectively. Note that, the resultant phase in Eq. (10) is wrapped between [-π, π]. In order to retrieve the object wave phase $\acute{A}_o$ two methods can be applied. The first method is to generate a digital reference wave by numerical means. While in the second method another measurement but without placing test sample has to be performed. Since we are looking for a fast method for phase retrieval, the reference wave field is numerically generated. Then Eq. (9) is multiplied with the reference wave model to retrieve the object wave field across the recording plane which is this case can be written as:

$$\acute{A}_o(\vec{x})=[A_O(\vec{x}).\ A_R^*(\vec{x}).\ A_R(\vec{x})](\vec{x}) \tag{11}$$