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Non-interferometric determination of optical anisotropy in highly-oriented fibres using transport intensity equation technique

T.Z.N. Sokkar[a], K.A. El - Farahaty[a,*], M.A. El - Bakary[a], M.I. Raslan[b], E.Z. Omar[a], A.A. Hamza[a]

[a] Department of Physics, Faculty of Science, Mansoura University, Mansoura, Egypt
[b] Department of Dental Biomaterials, Faculty of Oral and Dental Medicine, Delta University for Science and Technology, Gamasa, Egypt

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ABSTRACT

The optical setup of the transport intensity equation (TIE) technique is developed to be valid for measuring the optical properties of the highly-oriented anisotropic fibres. This development is based on the microstructure models of the highly-oriented anisotropic fibres and the principle of anisotropy. We provide the setup of TIE technique with polarizer which is controlled via stepper motor. This developed technique is used to investigate the refractive indices in the parallel and perpendicular polarization directions of light for the highly-oriented poly (ethylene terephthalate) (PET) fibres and hence its birefringence. The obtained results through the developed TIE technique for PET fibre are compared with that determined experimentally using the Mach-Zehnder interferometer under the same conditions. The comparison shows a good agreement between the obtained results from the developed technique and that obtained from the Mach-Zehnder interferometer technique.

1. Introduction

Recently, anisotropic materials are becoming the backbone of many everyday uses and industrial applications [1,2]. The anisotropic fibres refer to materials that their properties are directional dependent [1–3]. Generally, in fibre science, the optical and the structural properties such as the refractive indices and the birefringence act as a major source to characterize these fibres on the molecular level [4,5]. In which, the refractive indices and the birefringence of fibres enable us to obtain accurate information about the polarizability, molecular orientation and crystallinity [4–7]. Therefore, there is an urgent need for measuring these optical parameters with a high degree of accuracy. This accuracy mainly depends upon the values of the extracted phase objects.

Measurement of phase objects is considered as the main source to obtain an important information about an optical wavefield [2,7,8]. Phase objects have the key information of the refractive index, the surface profile and the birefringence of the fibre material [8,9]. Despite the importance of phase, it cannot be recorded by any type of recording devices (detectors). This is because, the detectors are based on turning the photons of the light into electrons and the electromagnetic field of these electrons are vibrated at rates ($\sim 10^{15}$ Hz and higher) consequently, there are no detectors to follow them [9]. Therefore, many experimental techniques whether it is interferometric [3,10] or non-interferometric [11,12] were proposed to retrieve the phase values and hence the optical and the structural properties of fibres.

Optical interferometer [3,13] is a family of techniques that are used to investigate the optical and structural properties of anisotropic fibres depending on the extracted phase values. Generally, to perform interferometric measurements, we need an optical setup in which two or more beams split from one light source and propagate into two different paths to interfere with each other [13]. The most common optical interferometric techniques include Pluta polarizing interference microscope [14], Fizeau interferometer [3,7], Michelson interferometer [13], Mach–Zehnder interferometer [2,13] and digital holography [4,15]. These techniques are characterized by a high degree of accuracy. But, it has a high sensitivity for the environmental conditions. The optical setup of some of them are relatively complex [2,4]. According to the interferometric systems setup, many algorithms, such as the spatial carrier frequency [2,8] and the temporal phase shifting [9,16], were proposed to extract the phase distribution of the tested fibre that hidden in the interference pattern. The spatial carrier frequency algorithm is considered as one of the most suitable techniques to extract the phase distribution from single shot interference pattern [4]. This algorithm calculates the phase of a pixel in an interference pattern relying on its surrounding pixels. One of the advantages of the spatial carrier frequency method is that it can be used to perform in-situ studies to record the fast varying effects on their actual time [2,4].

On the other hand, the non-interferometric techniques [17] are considered as one of the simplest optical techniques to extract the phase of a tested object and measure their optical properties. The transport

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

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intensity equation (TIE) technique [18] is one of the most accurate non-interferometric techniques to reconstruct the phase distribution and measure the refractive index. This technique was derived by solving a greens function for the phase inside of the circularly bound region [19]. Generally, the TIE technique is based on linking the phase of the optical wave field and the derivative irradiance (intensity). So, to extract the phase via TIE technique, three intensities images of the tested fibre at various defocusing depth are required [11,18], one of them is focused and the others are defocused. According to the experimental setup, TIE can be solved via different approaches. The simplest approach is to let the intensity distribution constant along the recorded planes. This approach is only valid for the case of captured pure phase objects. So that it is less applicable because the field from sample under test is merely propagated [19]. Paganin and Nugent [17] reported an approach for solving TIE for non-constant intensity distribution on detector plane. This approach helps to present a more general and applicable framework to determine the phase distribution for this case of the intensity distribution. The TIE technique can be applied using a partially coherent illumination and it does not need a complicated optical system setup [11,17,18].

Investigation of the refractive index profile for a test sample represents one of the major applications of the TIE technique [11]. Many authors used this technique to measure the refractive index of isotropic fibres [11,12]. But, unfortunately, the experimental setup of this technique is not ready to directly investigate the phase object and the refractive indices of anisotropic (birefringent) materials.

For that, other techniques for extracting anisotropy information and differentiating between the parallel and perpendicular polarization directions of anisotropic samples have been achieved. These technique include compensator-based [20,21] and polarimetric [22,23] methods. In case of the polarimetric methods, many optical components are needed to capture several images using polarization-analyzing optics. These components include rotators, polarizers and retarders [23]. This method is needed to considerable effort to extract the anisotropy information [22]. On the other side, the Brace-Köhler method [20] is considered common compensator-based techniques. This method is based on finding a minimum of intensity by rotating a calibrated compensator plate when the sample is observed through crossed-polarizers. The Brace-Köhler is applied only to low-level birefringence (partially-oriented fibres) [20,21].

In this article, we develop an experimental setup for the TIE technique to be suitable for investigating the optical properties of anisotropic highly-oriented fibres. The developed technique is used to investigate the refractive indices of PET highly-oriented fibres in the parallel and perpendicular polarization directions of light and hence the birefringence. To confirm the developed technique, the obtained results are compared with that determined experimentally using the Mach-Zehnder interferometer for the same fibre under the same conditions.

2. Theoretical considerations

2.1. Determination of the phase distribution of an anisotropic fibre using transport intensity equation (TIE) technique

The general format of the transport intensity equation (TIE) can be described by the following equation [18]:

$$\vec{\nabla}.\left[I(x,y;z)\vec{\nabla}\varphi(x,y;z)\right] = -k\frac{\partial I(x,y;z)}{\partial z} \tag{1}$$

In which, $\vec{\nabla}$ is 2D transverse gradient operator in $x-y$ plane, $I(x, y, z)$ and $\varphi(x, y, z)$ are the intensity and the phase of the optical wave field, respectively, k is the wave number and $\frac{\partial I(x,y;z)}{\partial z}$ is the intensity derivative. It can be determined experimentally using means of recorded intensities (two neighboring intensity plane) separated by small distance Δz by the following equation:

$$\frac{\partial I(x,y;z)}{\partial z} = \frac{I\left(x,y,z_0+\Delta z\right) - I\left(x,y,z_0-\Delta z\right)}{2\Delta z} \tag{2}$$

Paganin and Nugent [17] solved Eq. (1) for retrieving the phase object from the TIE at non-constant intensity distribution. According to this solution, the phase distribution of the object $\varphi(x, y)$ can be determined by the following equation:

$$\varphi(x,y) = \mathfrak{F}^{-1}\left[\frac{1}{k_x^2+k_y^2}\mathfrak{F}\left(k\frac{\partial I}{\partial z}\right)\right] \tag{3}$$

In which, $\mathfrak{F}$ and $\mathfrak{F}^{-1}$ are the Fourier transform and inverse Fourier transform operator, respectively and k_x and k_y are the spatial frequency in Fourier domain. Eq. (3) is the general case of isotropic fibres.

In case of anisotropic highly-oriented fibres, we used the microstructure model of highly-oriented fibres to differentiate between the parallel and perpendicular polarization directions for these fibres. According to this model, the majority of the molecular chains distribution are perfect highly oriented in parallel direction to the fibre axis. Therefore, this direction includes many crystalline regions. In other words, the highly-oriented fibres are built up of parallel array of identical fibrils which include a series of crystallites parallel to their symmetry axes. It follows the orientation distribution with respect to the fibre axis as shown in Fig. 1(I) [24].

In Fig. 1(I), when a polarized light beam vibrating parallel to the fibre axis, a large amount of light is transmitted through interplanar spaces which is equal or semi equal with little absorption. So, we obtained a maximum transmitted light beam T_{max}. In other words, we obtained a maximum intensity I_{max}. On the other hand, when a light beam falls with polarization perpendicular to the fibre axis, the majority of light is absorbed and scattered through the molecular chains. So, we obtained a minimum transmitted light beam T_{min}. So, we obtained a minimum intensity I_{min}.

Accordingly, the phase distribution of the tested highly-oriented fibre in the parallel polarization direction $\varphi^{\parallel}(x, y)$ and in the perpendicular polarization direction $\varphi^{\perp}(x, y)$ can be expressed by the following equation:

$$\varphi^{\parallel}(x,y) = \mathfrak{F}^{-1}\left[\frac{1}{k_x^2+k_y^2}\mathfrak{F}\left(k\frac{\partial I_{max}}{\partial z}\right)\right] \quad \& \quad \varphi^{\perp}(x,y) = \mathfrak{F}^{-1}\left[\frac{1}{k_x^2+k_y^2}\mathfrak{F}\left(k\frac{\partial I_{min}}{\partial z}\right)\right] \tag{4}$$

In order to accurately determine the direction of polarization with respect to the fibre axial direction, we carried out different experiments using interferometric techniques to study the intensity of light at different polarization directions. Table (1) demonstrates the intensity values obtained at different stretching stages using light sources of parallel and perpendicular polarization. According to this table, it is obvious that the parallel polarization direction has a maximum intensity transmitted through the fibre, while minimum intensity is recorded for the perpendicular direction of polarization. In addition, we noticed that arbitrary directions of polarization, other than parallel and perpendicular, have intermediate intensity values greater than the observed for the perpendicular direction and less than the intensity observed for the parallel direction. The polarization extinction ratio is calculated as a ratio between

Table 1
The transmitted intensity through an isotropic and an anisotropic samples in the parallel and perpendicular polarization directions.

	Transmitted intensity (arbitrary units)	
	Parallel polarization	Perpendicular polarization
Isotropic sample	106	104
Anisotropic sample	120	79