Scattered Light Measurement for the Birefringence Distribution Estimations

A.N. Vasilenko
,
I.U. Primak
, and
A.V. Khomchenko

Belarusian-Russian University, Mogilev, Belarus

DOI: 10.18502/ken.v3i3.2043

Abstract

The technique based on the digital processing of recorded scattered light distribution enabling for the measurement of the birefringence profile in non-uniform anisotropic materials was proposed.

1. Introduction

Studies of the light beam propagation in anisotropic optical windows are of greater interest because of a wide range of possible applications of these elements in optical devices as well as new fundamental physical mechanisms that are present in such samples. The measurement of birefringence of anisotropic samples becomes attractive in the case of using of non-uniform anisotropic materials, for example, of gradient-doped laser crystals or tempered glasses. In this point of view the polarimetry techniques, based on the photoelastic phenomena, are the certain interest for investigation of the mechanical stress in tempered glasses [1 - 7]. Such glasses are anisotropic and measurements of the intensity of polarized light transmitted through the sample under study allow one to estimate the stress-induced birefringence of optical glass plates. By measuring the light intensity distribution it can be analyzed and evaluated the birefringence for a single point or a small glass area, but this is still not good enough for a big anisotropic sample. The polarization-optical technique proposed in [8] allows visualizing the stress distribution in an extended area of the analyzed optical windows. However, usually the magnitude of residual stresses, and hence birefringence, has a non-uniform distribution in the sample thickness. Determination of surface stress requires the preliminary measuring of a central stress, which can be measured using, for example, analysis of light scattering by inhomogeneities in the distribution of the glass refractive index [9,10].
In this work, using the example of a study of tempered glass with a non-uniform thickness-distribution of the birefringence value, a technique for measuring the birefringence-induced phase difference profile of the electric vectors of linearly polarized components of optical radiation passing through a birefringent sample is presented.

2. Experimental details

This approach is based on recording of the spatial intensity distribution of the light scattered by inhomogeneities in the distribution of the glass refractive index. A typical experimental situation is simulated with the tempered glass parallelepiped stated along the vertical axis, making an angle of ππ /4 with the azimuth of the incident light polarization. Tempered glass plate is labeled as “sample” in the schematic diagram of experimental Setup showed in Figure 1. The thickness of glass plates varied in the range from 4 to 20 mm.

In a practical experimental setup we expected the value of residual-stress over the glass plate thickness is not constant, but a stress distribution in the plate thickness σσ (z) is described by [7,11]

$$\sigma(z)=\sigma_0(1-12(z/d)^2),\sigma(z)=\sigma_0(1-12(z/d)^2),$$

(1) where σ 00 is the maximum value of the tensile stress in glass and *d* is the thickness of the tempered glass plate.

Due to the non-uniform dependence of the residual stresses in the glass plate thickness the refractive index of tempered glass is also a function of the coordinates. It can be shown that the birefringence-induced phase difference in this case is given by

$$\delta=k_0\int_{-d/2}^{d/2}(n_1(z)-n_2(z))dz\delta=k_0\int_{-d/2}^{d/2}(n_1(z)-n_2(z))dz$$

(2) or

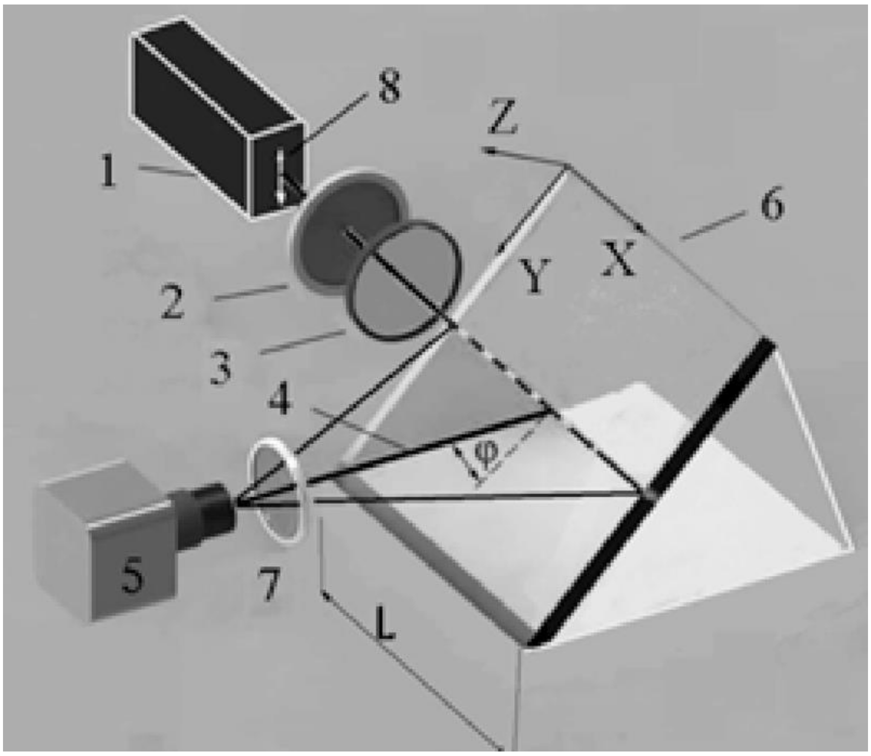
$$\delta=k_0C\int_{-d/2}^{d/2}(\sigma_1(z)-\sigma_2(z))dz,\delta=k_0C\int_{-d/2}^{d/2}(\sigma_1(z)-\sigma_2(z))dz,$$

(3) where k_0k_0 is wave number of vacuum, *n* 11 and *n* 22 are the refractive indices along the slow and fast axes, respectively, $\sigma_1\sigma_1$ and $\sigma_2\sigma_2$ are principal stresses, CC is a photoelastic constant of glass.

In order to determine σ 00 and to obtain the dependence of *n* 11 (*z*) and *n* 22 (*z*) the measurement of the spatial distribution of the scattered light intensity is performed using scan of glass plate by a narrow beam in its cross-section along Z - axis, and the subsequent processing of the distribution of the light intensity scattered by the inhomogeneities of the refractive index in glass is made [12]. To achieve this, we propose to use the experimental setup that allows visualizing propagation of light beam in anisotropic sample. In this case analyzing intensity distributions of scattered light it is possible to study almost locally anisotropy of the glass refraction index. The light beam goes through polarizer, lens and a normal-incidence face of glass plate 6. The laser light at 533 nm with intensity of 1 mW is produced by the solid-state laser 1. The light is collimated by lens 3 to a beam width of about 180 μμ m diameter and is linearly polarized at π/4 rad from the optical axis of the sample by passing through a polarizer 2. Existence of refraction index fluctuations small in comparison with a wavelength of the probing radiation is the reason of light scattering in the tempered glass [9]. The areas of such fluctuations, having small size in comparison with the light wavelength, work as dipoles, scattering light in the direction, which is normal to the X - axis (see Figure 1).

Figure 1

Experimental Setup used for determination of optical parameters of tempered glass: 1 - light source, 2 - polarizer, 3 - lens, 4 – beam splinter, 5 – CCD camera, 6 – sample, 7 – filter, 8 – the direction of polarization orientation of the radiation which passed through the polarizer.



It is known that if the observation direction is perpendicular to the direction of polarization of the input light then the intensity of the scattered light is defined as [9]

$I_{\perp}(z,x)=I_0\cos^2[0.5k_0C\sigma(z)x]$,I⊥(z,x)=I0cos2[0.5k0Cσ(z)x],

(4) where I_0I0 is the intensity of input light beam.

In experimental setup the intensity distribution of scattered light is recorded in a plane, which is perpendicular to the direction of its propagation, by a photorecording device 5 (CCD camera).

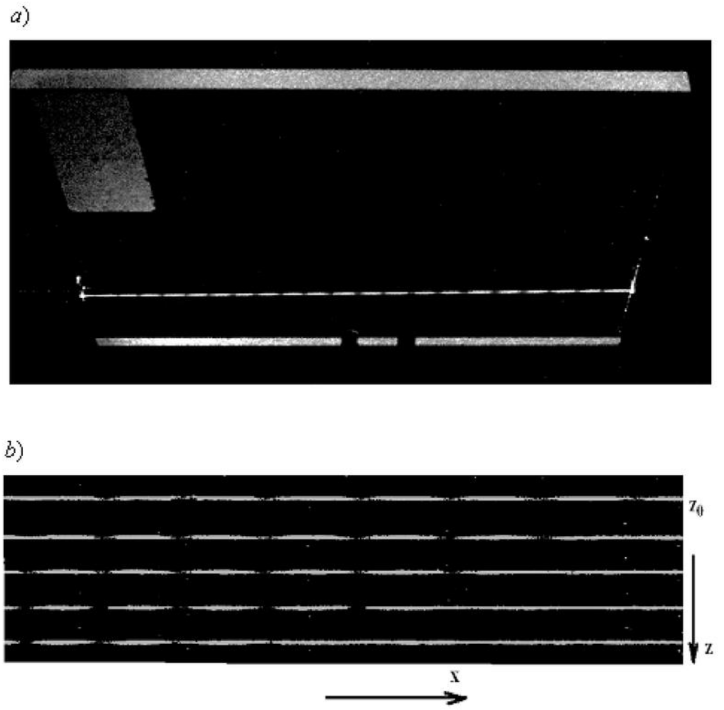
3. Results and discussions

Because ordinary and extraordinary waves have various phase velocity in anisotropic material, between them there is a phase delay. The interference of ordinary and extraordinary waves changes a condition of polarization states of light beam at its distribution along the sample. Spatial modulation of scattered light surely is recorded in the direction which is perpendicular to the direction of propagation of the probing radiation in a anisotropic sample (Figure 2,*a*). In this case the phase difference $\delta = \pi$ arises on the length *x*, equaled to the period of the regular distribution intensity of scattered light.

As distribution of mechanical stress in glass in direction of Z- axis $\sigma(z)$σ(z) has a parabolic type, that is represents actually a lens, at propagation of light beam in the OX direction (see Figure 1) it will deviate in the direction of the refraction index increase, as is registered on an experiment. As when scanning the glass plate along Z - axis the light beam gets to areas with different refraction index and it deviates to the sample surface on different length x_ii . In this case the spatial modulation of scattered light which noticeable in the direction perpendicular to the light propagation direction in anisotropic sample and which caused by interference between ordinary and extraordinary waves at their distribution in an sample, stops at various values of *x* coordinate.

Figure 2

Space modulation of scattered light (*a*) and changes in intensity distribution of scattered light along the sample (*b*) at its scanning in direction of Z- axis.



The imposed pictures of spatial modulation obtained at various coordinates of the input point of radiation in glass plate z_0 are given in Figure 2. The analysis of the recorded distributions of *I*(*z*, *x*) (see Figure 2,*b*), obtained when scanning the sample by the light beam in direction of Z - axis showed in Figure 1, allows to receive estimates of $\sigma(z)$ dependence.

According to [11] the stress profile in the tempered glass is described by a parabolic function. Only in the case of full compliance with the conditions of the quenching technology, it has the form (1). In practice, this is usually not performed. Therefore we represent the stress profile for glasses by function

$$\sigma(z)=A_p z^p+A_{p-1}z^{p-1}+...+A_1 z^1+A_0.$$

(5)

The values of the coefficients A_i (*i* = 1, 2,..., *p*) can be found by analyzing the magnitude of the beam deflection when it propagates through the glass plate parallel to the X-axis. Analysis of the recorded distributions (Figure 2 *b*), constructed by scanning the sample with a light beam along the Z-axis, allows to analyze the magnitude of the ray deflection when it propagates parallel to the X-axis (Figure 3) and estimate the function σ (z). In Figure 3the glass area is marked by blue line. It is very good know the ray deflection is described by equation [12]

$$\frac{d^2z}{dx^2}=\frac{1}{n(z)}\frac{dn}{dz},$$

(6) where $n(z)$ and $\frac{dn}{dz}$ are function and its derivative describing the distribution of the refractive index through the thickness of the glass. Assuming, in the equation (6)

$$1/n(z)\approx 1/n_0,$$

$$\frac{dn}{dz}=C(pA_pz^{p-1}+(p-1)A_{p-1}z^{p-2}+\ldots+A_1)$$

(7) and taking into account the boundary conditions $z=0$ and $dz/dx=0$ at $x=0$ we obtain the solution of equation (6):

$$\int_0^{z'}\frac{dt}{\sqrt{2Cn_0^{-1}\{A_p[(z_0+t)^p-z_0^p]+A_{p-1}[(z_0+t)^{p-1}-z_0^{p-1}]+\ldots+A_1t\}}}=x,$$

(8) where x is the ray propagation length at which this deviation z' from the ray entry point in the glass z_0 is obtained, n_0 is refractive index of isotropic glass.

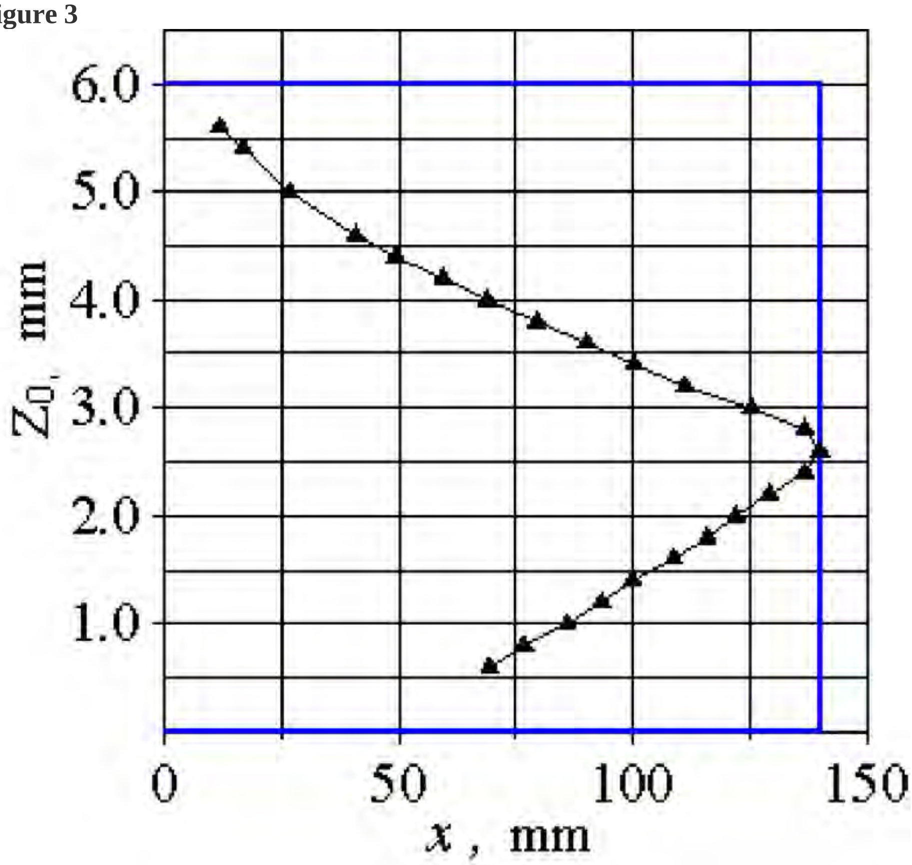
The integral on the left-hand side of equation (8) is an improper integral of type 2, which permits regularization. Obtained solution allows us to determine the unknown coefficients A_i by the least squares method based on the results of recording the trajectory of the light ray in the glass. The minimized functional has the form

$$F(A_1,A_2,\ldots,A_p)=\sum_j(x_j-x(z'_j,A_1,A_2,\ldots,A_p))^2,$$

(9) where x_j is the ray propagation length at which this deviation z'_j from the ray entry point in the glass z_0 is obtained (see Figure 3).

In the simplest case of the dependence $\sigma(z)=A_2z^2+A_1z^1+A_0$, the solution of equation (6) is analytic. It should be noted that the coefficient A_0 can be determined, for example, by analyzing the periodic dependence (4). Numerical simulation of the propagation of light in the glass and processing of recorded radiation using the least squares method demonstrated the possibility of determining the coefficients A_i with an error of less than 10%.

Figure 3



The dependence of the distance *x* versus the coordinate of input point of the light beam z_0 into the glass sample with 6 mm thickness.

The estimate of the stress $\sigma_0$0 can be obtained on the basis of an analysis of the recorded spatial distribution of the intensity of the scattered light $I_\perp(z_m,x)$I⊥(zm,x) ($z_m$zm is maximum tensile stress point). As follows from the data presented in Figure 2, this dependence $I_\perp(z_m,x)$I⊥(zm,x) is periodic. In this case, the stress $\sigma_0$0 and the period *T* of a function $I_\perp(z_m,x)$I⊥(zm,x) , which corresponds to the rectilinear propagation of light in the glass, are connected by the relation

$\sigma_0=2\pi/(k_0CT)$.σ0=2π/(k0CT).

(10)

In accordance with the results of data processing presented in Figures 2 and 3, the intensity distribution has period *T* = 6.1 mm at *z* $_m$m = 0.4 mm. The estimated value of the $\sigma_0$0 stress is 48 MPa. Taking into account the above, the values of the compressive stresses at the glass surfaces are -340 MPa and -318 MPa respectively. The obtained values of the residual compressive stresses on the glass surface and the maximum tensile stress make it possible to reconstruct the profile of mechanical stresses in the cross section of the sample.

4. Conclusions

This work demonstrates that the using the analysis of the recorded intensity distribution of scattered light it is possible to estimate mechanical stress in the tempered glass and to investigate their asymmetric distribution in a cross-section of glass plate and to make estimates of values of the stretching and squeezing stress in glass and also the surface stress. It is shown that distribution of residual stresses in the tempered glasses is significantly the non-uniform. Obtained results show a good agreement with the theoretical calculation dates for central area of the glass plate. When moving away from the central area of the glass plate to its surface we observe the deviation of the refractive index profile from parabolic form. The presented results indicate that spatial distribution of birefringence-induced phase difference in non-uniform anisotropic materials can be correctly measured using the offered approach.

References

[1] Bouchal, P. Polarization sensitive phase-shifting Mirau interferometry using a liquid crystal variable retarder / Petr Bouchal, Radek Celechovsk, and Zdenek Bouchal // Optics Letters. – 2015. – Vol. 40, № 19. – P. 4567-4570.

[2] A new method for tempering stress measurement in glass panels / H. Aben [at al] // Estonian J. of Engineering. – 2013. – Vol. 19, № 4. – P.292–297.

[3] Helen, S. S. Achromatic phase shifting by a rotating polarizer / S. S. Helen, M. P. Kothiyal, R. S. Sirohy // Optics Communications –1998.– Vol.154. № 5-6.– P.249-254.

[4] Full-field heterodyne polariscope with an image signal processing method for principal axis and phase retardation measurements / Yu-Lung Lo [at al] // Applied Optics – 2006 - Vol. 45, №. 31 - P. 8006-8012.

[5] Ajovalasit, A. Measurement of edge residual stresses in glass by phase-shifting mesthod / Ajovalasit A., Petrucci G., Scafidi N. // Optics and Lasers in Engineering – 2011.- Vol. 49, № 5. - P.652-657.

[6] Calvert, G. Applications of modern automated photoelasticity to industrial problems / Calvert,G., Lesniak J., Honlet M. // Insight -2002.-Vol. 44 № 4. - P.1-4.

[7] Kumar, Y. P. Opaque optics thickness measurement using a cyclic path optical configuration setup and polarization phase shifting interferometry / Y. Pavan Kumar and Sanjib Chatterjee // Applied Optics. – 2012. – Vol. 51, № 9. – P1352-1356.

[8] Khomchenko, A.V. Polarizing interferometry of environments with linear two-refraction / A.V. Khomchenko, I.U. Primak, A.N. Vasilenko // Procceding of Applied Optics – 2016. St. Peterburg. 2016. - P.213-217.

[9] Hödemann, S. Scattered laser light fringe patterns for stress profile measurement in tempered glass plates / S. Hödemann [at al] // European Journal Glass Scientific Technology, A. -2014. –Vol. 55, №3, - P.90-95.

[10] Gradient scattered light method for non-destructive stress profile determination in chemically strengthened glass / S. Hödemann [at al] // Journal Mater Scientific, – 2016. –Vol.51, -P.5962–5978.

[11] Stress profile measurement in axially symmetric glass sample / N. Kreemer [at al] // Ceramics - Silikaty. – 2008. –Vol.*52,* № 3. – P. 183-187.

[12] Born, M. Principles of optics / M. Born, E. Wolf – N. Y.: Pergamon Press, 1975.