Measurements of stress-optic coefficient in polymer optical fibers

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Abstract: We have systematically measured the differential stress-optic coefficient, ΔC, in a number of PMMA fibers drawn with different stress, ranging from 2 up to 27 MPa. ΔC was determined in transverse illumination by measuring the dependence of birefringence on additional axial stress applied to the fiber. Our results show that ΔC in PMMA fibers has a negative sign and ranges from -4.5 to -1.5×10^{-12} Pa^{-1} depending on the drawing stress. Increase of the drawing stress results in greater initial fiber birefringence and lower ΔC.

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Development of polymer optical fibers has opened new application opportunities in optical communication [1] and sensing [2] because of their low cost, easy handling and very good flexibility. Optical anisotropy in polymers of different types has been investigated for many years due to their potential use in various photonic devices [3, 4]. Although PMMA is a very popular polymer widely used for industry, there are many inconsistencies in the literature concerning its differential stress-optic coefficient $\Delta C = C_2 - C_1$. Measurements performed in PMMA discs (18mm diameter, 10mm thick) showed ΔC equal to -3.3×10^{-12} Pa^{-1} [4], but in [5] the measurements carried out in discs of different size (13.03 mm diameter, 2.85mm thick) gave a value of $\Delta C = 5.5\times10^{-10}$ Pa^{-1}. Another quite different result was reported in [6], $\Delta C = -1.08\times10^{-10}$ Pa^{-1}. Very systematic studies of the optical and mechanical properties of bulk PMMA (Plexiglas 55) are presented in [7]. In particular, the strain-optic

coefficients for this material have been measured $p_{11}=0.300$, $p_{12}=0.297$, which lead to a calculated value of $\Delta C = -2.4 \times 10^{-12}\,\text{Pa}^{-1}$, assuming the following material constants: refractive index $n=1.4928$ at $\lambda = 656$ nm [7], Young's modulus $E = 2.8 \pm 0.2$ GPa [8], and Poisson's ratio $\nu = 0.345$ [9].

The goal of this work was to systematically measure the coefficient $\Delta C = C_2 - C_1$ in a number of PMMA fibers drawn with different stress and to investigate the effect of temperature annealing on this parameter. To determine ΔC, we measured the dependence of fiber birefringence upon additional axial stress $\sigma_z^{applied}$ applied to the fiber . The drawing stress and geometrical parameters of the examined fibers are gathered in Table 1. The fibers used in this study were all drawn from homogeneous, nominally pure PMMA rods obtained from AMARI plastics. The mean molecular weight was determined by gas permeation chromatography to be 87 000. To prevent the preforms from bubbling in the draw tower oven, they were annealed at 80°C for 48 hours immediately prior to fiber drawing. The fibers were all drawn with a hot-zone temperature of 181 ± 2°C and the fiber tension and consequently the drawing stress controlled by adjusting the preform feed and fiber take-up rates. A selection of the fiber samples was annealed at 100°C for 20 hours.

To measure the fiber birefringence in the direction perpendicular to the symmetry axis, we used a system employing a Senarmont compensation principle shown in Fig.1. The measured retardation distribution $R(x)=\Sigma_x(x)-\Sigma_z(x)$ is related to the axial stress distribution $\sigma_z(r)$ in the fibers cross-section by the inverse Abel transformation [10]:

$$\sigma_z \left(r\right) \Delta C = \frac{-1}{\pi} \int_r^{r_0} \frac{dR(x)/dx}{\sqrt{x^2 - r^2}} dx \, , \qquad (1)$$

where r_0 is the fiber radius, $\sigma_z(r)$ is the axial stress, and dR/dx is a derivative of measured retardation. The stress optic coefficient ΔC can be easily retrieved by applying increasing axial load to the fiber and finally by plotting the dependence $\Delta C \sigma_z^{calculated}$ versus $\sigma_z^{applied}$ with ΔC being a proportionality coefficient. Due to cylindrical symmetry, stress induced optical anisotropy of the fiber is characterized by three principal indices n_z, n_r, n_θ. When axial stress is applied to a fiber made of uniform material, radial and tangential stress components in the fiber cross section are significantly lower than σ_z $(\sigma_z >> \sigma_r, \ \sigma_z >> \sigma_\Theta)$, which results in:

$$n_z = n + C_1\sigma_z, \qquad n_\Theta = n + C_2\sigma_z, \qquad n_r = n + C_2\sigma_z. \qquad (2)$$

and finally

$$n_x - n_z = \Delta C\sigma_z, \qquad (3)$$

where $\Delta C = C_2 - C_1$ is the differential stress-optic coefficient and $n_x = n_\Theta = n_r$. As the investigated fibers are made of uniform PMMA, the inverse Abel transformation of the measured retardation distribution R(x) provides directly information about the birefringence $n_x - n_z$ induced by applied axial stress.

We first measured ΔC in a standard SMF-28 silica fiber, which was used as a reference to test our measurement and processing method. Silica is a very well characterized material, thus allowing us to compare the results obtained using our method with a reliable value obtained from the literature [11], $\Delta C = (3.57\pm0.03)\times10^{-12}$ Pa^{-1} at 526 nm. By the linear fitting of measured fiber birefringence in the pure silica cladding versus applied stress, we obtained a value for the stress-optic coefficient of $\Delta C = (3.52\pm0.01)\times10^{-12}$ Pa^{-1}. The measured value is not significantly different from the one reported in the literature, which gives confidence in our measurement and processing methods.

Similar measurements were performed for a series of PMMA fibers drawn with different stress (Table 1). In Fig.2 we show the birefringence distribution reconstructed from the retardation measured for different axial stress $\sigma_z^{applied}$ applied to fiber 1b, which was drawn using a relatively small drawing stress of 1.86 MPa. For all investigated fibers, the applied axial stress was gradually increased until the fiber broke. As it can be clearly seen in Fig.2, the reconstructed distribution of stress–induced birefringence $\Delta C\sigma_z$ is not perfectly uniform in the fiber's cross-section. An increase of $\Delta C\sigma_z(r)$ near the fiber edges by about 10% is most probably caused by the higher cooling rate of the external layers of the fiber during the drawing process. To determine ΔC in the polymer fibers, we averaged the measured distribution of $\Delta C\sigma_z(r)$ in the fiber cross-section and plotted the dependence of the averaged $\sigma_z\Delta C = n_x - n_z$ as a function of applied stress, see Fig.3. In order not to obscure this figure, we show only the results obtained for a few fibers having significantly different ΔC. The birefringence induced by applied axial stress increases linearly for small values of $\sigma_z^{applied}$. The stress optic coefficient ΔC was determined for each PMMA fiber by linear approximation of the dependence of $\Delta C\sigma_z^{calculated}$

(averaged over the fiber cross-section) versus $\sigma_z^{applied}$ for small values of $\sigma_z^{applied}$, with ΔC being a regression coefficient. The dependence of the stress-optic coefficient ΔC upon drawing stress is presented in Fig.4. The value of ΔC increases against $\sigma_{drawing}$ from -4.5 to -1.5×10^{-12} Pa^{-1} in a nonlinear manner and appears to gradually saturate for high drawing stress. The same measurements were repeated for the fibers annealed at a temperature of 100°C for 20 hours. It is interesting that fiber annealing does not change the general trend in the dependence of ΔC versus $\sigma_{drawing}$, however the saturation effect for annealed fibers occurs at a greater absolute value of ΔC.

Finally, we show in Fig.5 the dependence of ΔC upon residual fiber birefringence, which is clearly linear with no significant impact of the annealing process. This experimental result shows that the absolute value of the stress optic coefficient ΔC decreases in the PMMA fibers having greater initial birefringence, which directly corresponds to a greater initial ordering of molecules. As the trend line shown in Fig.5 takes a value of -4.8×10^{-12} Pa^{-1} at zero birefringence, we can estimate ΔC for the bulk PMMA used to draw the fibers, $\Delta C=-4.8\times10^{-12}$ Pa^{-1}.

From the series of experiments reported in this letter we conclude that the stress-optic coefficient ΔC in PMMA fibers has negative sign and ranges from -4.5 to -1.5×10^{-12} Pa^{-1} depending on the drawing stress The dependence of ΔC on drawing stress is nonlinear and gradually saturates at greater $\sigma_{drawing}$. Annealing has a significant impact on the dependence of the differential stress-optic coefficient on $\sigma_{drawing}$. Moreover, our measurements demonstrate that ΔC is linearly proportional to initial fiber birefringence with annealing having no impact on the slope of this dependence.

References

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Tab.1. Parameters of the investigated fibers. All annealed fibers are indicated by an apostrophe.

Annealing temperature was 100°C and duration 20 h.

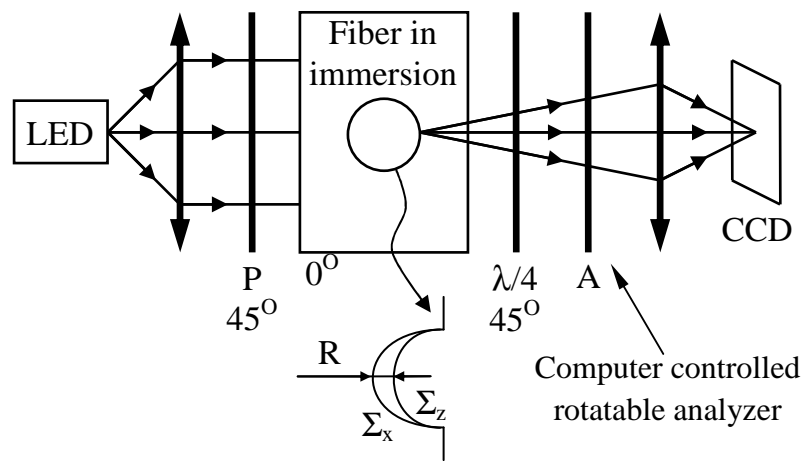| Fiber sample	Measured diameter [mm]	$\sigma_{drawing}$ [MPa]	Measured ΔC [Pa^{-1}]	Measured initial birefringence
1a'	0.605	1.98	-4.3×10^{-12}	$- 1.05 \times 10^{-4}$
1a	0.556	2.34	-4.37×10^{-12}	$- 1.44 \times 10^{-4}$
1b'	0.329	8.86	-3.45×10^{-12}	$- 3.71 \times 10^{-4}$
1b	0.387	5.85	-3.62×10^{-12}	$- 3.23 \times 10^{-4}$
1c'	0.126	21.3	-2.78×10^{-12}	$- 5.61 \times 10^{-4}$
1c	0.105	27.2	-1.54×10^{-12}	$- 7.91 \times 10^{-4}$
1d'	0.396	11.4	-3.20×10^{-12}	$- 4.19 \times 10^{-4}$
1d	0.294	18.7	-1.79×10^{-12}	$- 7.91 \times 10^{-4}$
1e'	0.291	21.2	-3.16×10^{-12}	$- 5.27 \times 10^{-4}$
1e	0.263	23.1	-1.78×10^{-12}	-8.18×10^{-4}

Fig.1. Experimental set-up for measuring retardation distribution, $\lambda = 526$ nm
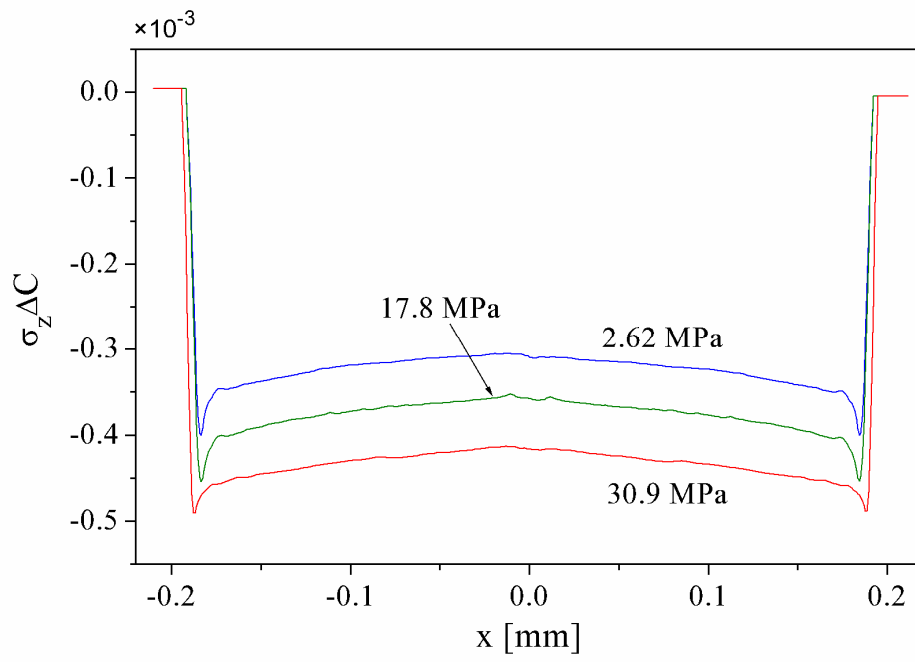
Fig. 2. Distribution of birefringence $\sigma_z \Delta C = n_x - n_z$. reconstructed from measured retardation for different values of applied axial stress $\sigma_z^{applied}$ in the PMMA fiber indicated as 1b.
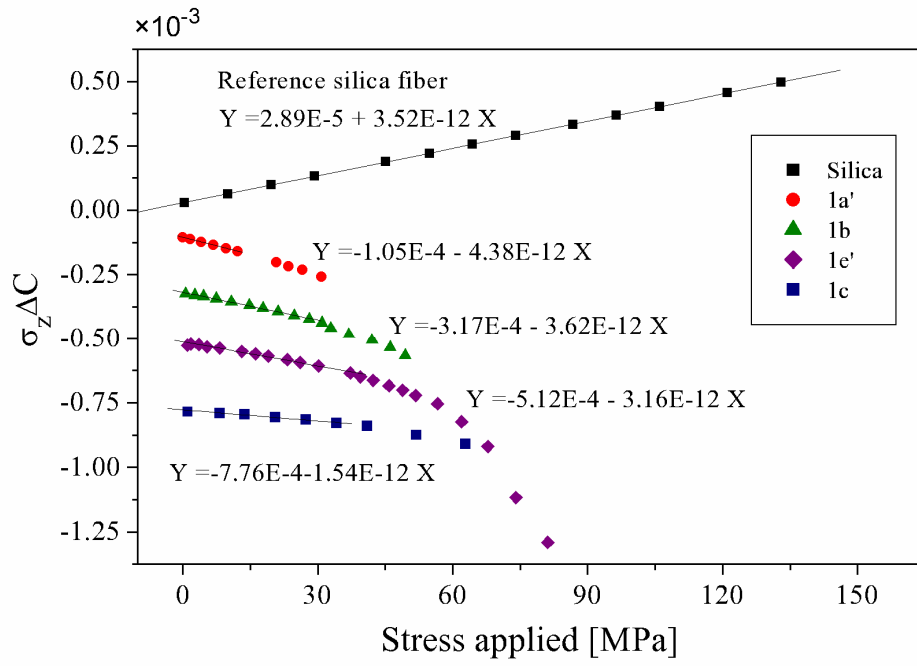
Fig. 3. Dependence of birefringence $\sigma_z \Delta C = n_x - n_z$. in selected PMMA fibers versus applied axial stress. The stress-optic coefficients ΔC were obtained by fitting to the linear part of the measured characteristics.
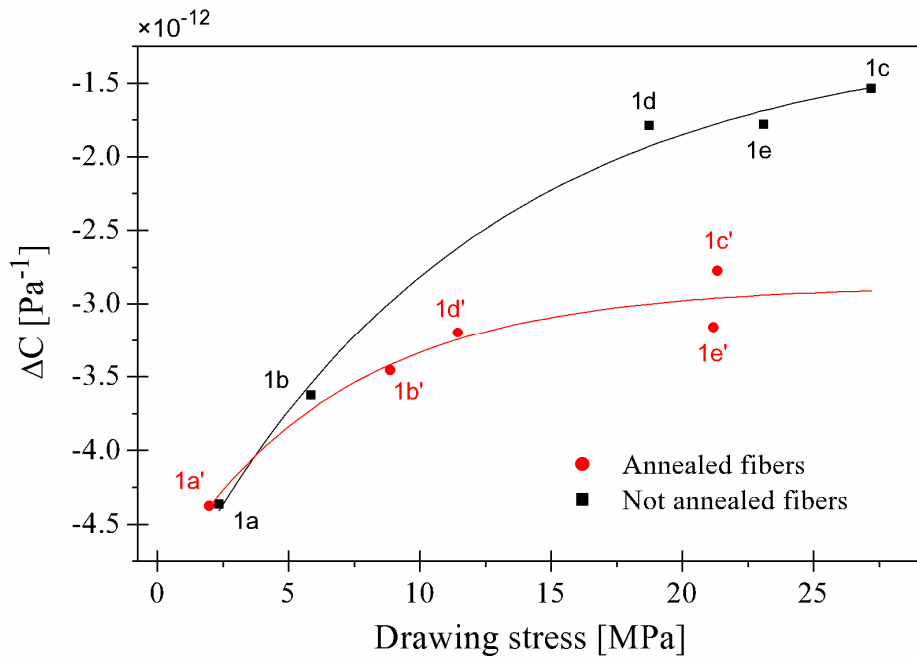
Fig. 4. Dependence of the stress-optic coefficient upon drawing stress in the PMMA fibers. Measurements before and after annealing were carried out for fibers with different cross-sections and as a result the drawing stress for corresponding fibers is not the same.
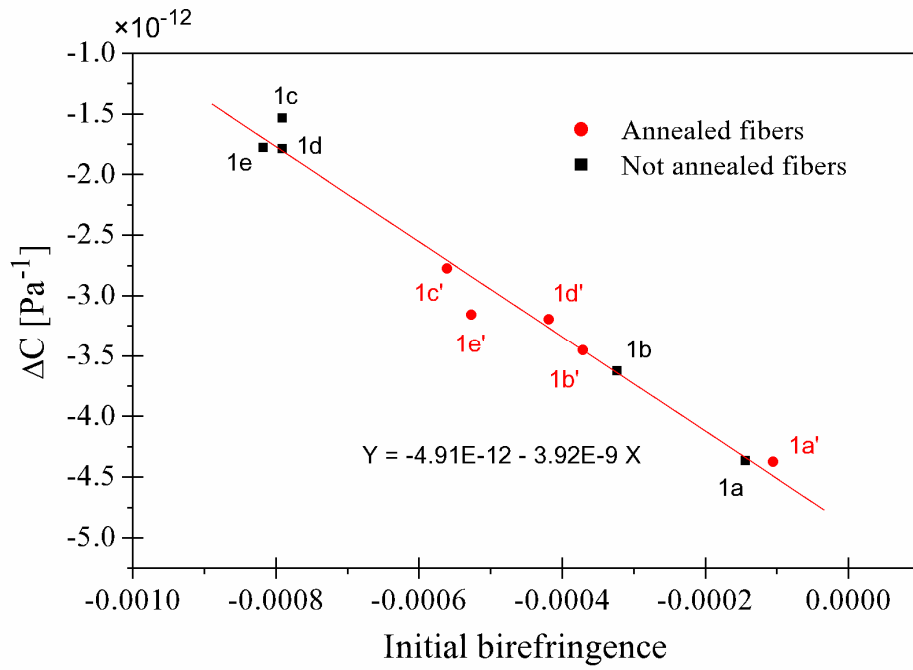
Fig.5. Stress optic coefficient as a function of initial fiber birefringence for the PMMA fibers from Table 1. Measurements before and after annealing were carried out for fibers with different cross-sections and as a result the drawing stress for corresponding fibers is not the same.