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REFRACTIVE INDEX METROLOGY OF OPTICAL POLYMERS

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Abstract

Possible optical applications of polymer materials are defined mainly by their index of refraction, determined with sufficiently high accuracy. Proper choice of measuring technique depends on the material, sample size and thickness. We have examined various types of optical plastics in the form of bulk bodies as well as thin film layers. Different methods were applied to measure their refractive index values at a number of wavelengths in the visible and near-infrared regions. Classical refractometry as well as a goniometric set-up with laser illumination or white lightning source with interference filters have been used to measure bulk samples. Additionally, two types of laser microrefractometers were assembled to receive accurate data in case of thin films. Detailed metrological analysis is presented.

Reported refractive and dispersive data as well as proposed measuring techniques are useful in polymer applications in the design of contemporary optical systems.

Key words: *optical polymers, refractive index, refractive index metrology*

1. INTRODUCTION

Polymer materials are presently used in the design and fabrication of consumer as well as precise optical instruments. In photonic applications they offer advantages over optical glasses including low cost and weight, high impact resistance, and ability to integrate proper mechanical and optical features (Menendez, Erismann & Gauvin 1999). Optical polymers (OPs) manufacturing includes lenses for video and still cameras, projection televisions, compact disk drives, light-emitting diodes, printers and bar-code readers, biomedical optics and ophthalmic lenses, light-guides, optical films, high-density optical storage media, diffractive optics, flat panel displays, metallized reflectors, optical fibers, couplers, and connectors for optical communication networks. Great economies are possible through usage of OPs for reproducing aspheric and other complex geometric surfaces, which are costly to produce in glass, as well as in the production of miniature optical elements, necessary in medical vision applications, as laparoscopes, arthroscopes, cystoscopes, endoscopes, etc., (Keyes et al. 2001, Beich 2002, Tolley 2003).

Nano optical, bio-optical and nanomedical devices are under intensive development. Photonics technology is focused on surgical nanodevices, cell's imaging systems, cancer detection nanostructures, and novel therapeutic micro-manipulating instruments. Nanotechnology has a revolutionary impact on biomedical applications such as drug delivery, biomarking, cancer diagnosis, bioprobing, and nanotherapy. Fluorescent polystyrene nanospheres have already been used to monitor the epidermal growth factor. Some nanostructures such as nanotubes and polymer nanoparticles can be applied as luminescent biomarkers and transporting nano-vehicles to cancer tissues or tumor cells. A number of hybrid nanospheres have been fabricated for biomedical applications as targeted drug delivery, magnetic-resonance contrast agents, separation of biomolecules, and photonic biosensors (Nikolov 2007).

Optical plastics are clear polymers that provide excellent light transmission in the visible (VIS) and near-infrared (NIR) regions (Sultanova, Kasarova & Nikolov 2013). Photonic applications of OPs require also the knowledge of their precise refractometric and dispersive characteristics. The measuring principles and procedures for determination of refractive properties of OPs are quite different. Refractive indices of transparent organic plastic materials can be obtained using the standard U.S. test method (National Bureau of Standards 1961) in which the well-known Abbe refractometer is utilized. It operates with a source of white light and Amici prisms as colour compensators. The refractive index value for the sodium D lines can be read directly from the instrument. The Abbe instrument is convenient when small plastic specimens are examined, but its accuracy is not acceptable for modern optical design projects. SCHOTT Company applies mainly two refractive index measuring techniques to obtain precise data of optical glasses (SCHOTT Glass Technologies 2013). They use a V-block refractometer and a spectral goniometer, but both methods require large glass samples, nearly square or prism shaped. However, polymer optical elements may appear as bulk bodies with various dimensions as well as thin polymer layers on different substrates. Our previous results show that bulk specimens differ in refractive properties compared to thin polymer emulsions (Sultanova, Kasarova & Nikolov 2012) and they should be studied separately. Most efficient in the latter case are laser measurements of film refractive indices. Therefore, special techniques are required to obtain precise refractive data of studied polymers.

In this paper we present a more effective classical refractometric method for index measuring of bulk polymer samples in the VIS range. Additional goniometric set-up is proposed for the entire VIS and NIR spectrum which may be accomplished also with laser illumination. Three-wavelength or four-wavelength microrefractometer is used to measure thin polymer specimens. We have studied optical properties of various types of plastics, including principal and some new development polymers. The principal OPs are polymethyl methacrylate (PMMA), polystyrene (PS), polycarbonate (PC), methyl methacrylate styrene copolymer (NAS), styrene acrylonitrile (SAN), and methylpentene (TPX) (Horne 1983, U.S. Precision Lens Incorporation 1973). Chemical companies fabricate different trade-marks of OPs as NAS-21 Novacor, CTE-Richardson, Zeonex, Optorez, Bayer, etc. Control samples produced by the American Eastman Chemical Company (ECC) are also examined. Metrological analysis of the proposed measuring techniques is accomplished.

2. REFRACTIVE INDEX MEASUREMENTS OF BULK POLYMER SAMPLES

2.1. Classical refractometric method

Measurements of refractive indices of bulk polymer samples were carried out with the Zeiss Pulfrich refractometer (PR2) using its V-type SF3 glass prism (VoF3 prism) (Carl Zeiss JENA 1976). The standard total internal reflection prism is not convenient for index measurements of OPs, since it requires thick cubic specimens. We have used injection moulded plates of the examined polymer materials with thickness from 2.54 mm to 5.1 mm having two fairly well polished, mutually perpendicular surfaces to obtain good refractometric data. The covered prism with studied polymer sample inside was firmly fixed on the PR2 instrument. The thermostatic housing of the VoF3 prism allowed us to maintain and regulate measuring temperature with stability of 0.1 °C. Proper immersion emulsions have been used to ensure the optical contact between polymer plates and SF3 glass. We used a saturated aqueous solution of zinc chloride (n_e =1.51) and silicon oil (n_d = 1.56) for low refractive OPs as PMMA, and a saturated water solution of potassium-mercuric-iodide with n_e = 1.73 for higher refractive materials as PS, PC, etc. The prism cap is made of stainless steel and has mirrored internal surface to avoid evaporation of matching liquids as well as to cut down temperature fluctuations in the polymer sample. Further details on the measuring method are included in our paper (Sultanova, Nikolov & Ivanov 2003).

Refractive indices in VIS light of studied OPs at the emission wavelengths of the spectral lamps of the PR2 instrument are obtained, namely, at green e-line 546.07 nm and blue g-line 435.83 nm (mercury lamp), yellow d-line 587.56 nm (helium source), and blue F-line 486.13 nm and red C-line 656.27 nm (hydrogen lamp). Some of the results at measuring temperature of 20 °C are included in Table 1. Abbe numbers ν_d (SCHOTT Glass Technologies 2013, Sultanova, Nikolov & Ivanov 2003) of OPs are calculated by the obtained experimentally index data.

2.2. Goniometric method for the VIS and NIR region

A goniometric set-up was assembled to measure refractive indices of bulk polymer samples in the entire VIS and NIR region up to 1052 nm. The optical scheme was reported in (Sultanova Nikolov & Ivanov 2003, Kasarova et al. 2007) and it is similar to the set-up presented in Figure 1, excepting the illumination part. A G5-LOMO goniometer with an accuracy of one arc second was used with the VoF3 prism-measuring block, positioned on the G5 test table. The polymer samples were placed and covered in the prism. The lighting module consists of a 250 W halogen lamp and Carl Zeiss metal interference filters in the region from 548 nm to 1052 nm. A silicon photo detector device was applied with operating amplifier and indicator (see Fig. 1). The collimated beam from the lighter falls perpendicularly to the entrance surface of the prism. The right-hand collimator with the attached photo detector determines the measuring angle α. The angle of deviation γ is formed by the sample located inside the V-shaped prism. The refractive index n_λ of the examined polymer at given wavelength λ is calculated as follows:

$$n_\lambda^2 = N_\lambda^2 - \cos\gamma\sqrt{N_\lambda^2 - \cos^2\gamma}, \quad \gamma = 90^o - \alpha, \qquad (1)$$

where N_λ is the refractive index of the VoF3 prism glass, γ is the calculated angle of the deviated beam, and α is measured by the G5 goniometer. The index N_λ of SF3 glass is determined by the data published in (SCHOTT Glass Technologies 2013, Carl Zeiss JENA 1976) for standard spectral lines. Jena glass and SCHOTT glass are almost equal for SF3 type to the fourth decimal place. Results at measuring temperature of 20 °C for some of the studied OPs are presented in Table 1. Obtained data confirms that plastics have a limited range of refractive index values between 1.49 ÷ 1.62. Abbe numbers ν_d are given in the last column and comparison of dispersive properties of OPs is possible. High refractive materials as PC or PS have lower value of ν_d. In our previous investigations (Sultanova, Kasarova & Nikolov 2013) we present results of Abbe numbers ν_{879} in the NIR region which confirm lower dispersion of OPs in this part of the spectrum, even smaller than dispersion of some optical glass types.

Table 1. Refractive characteristics of bulk OPs.

OP material	Wavelength (nm)							ν_d
	435.8	546.1	587.6	632.8	703	879	1052	
PMMA	1.5025	1.4934	1.4914	1.4890	1.4863	1.4839	1.4813	59.2
PS	1.6171	1.5963	1.5917	1.5872	1.5821	1.5767	1.5718	30.5
PC	1.6117	1.5896	1.5849	1.5802	1.5749	1.5695	1.5645	29.1
SAN	1.5882	1.5705	1.5667	1.5626	1.5579	1.5536	1.5496	35.4
NAS-21	1.5933	1.5753	1.5714	1.5683	1.5643	1.5582	1.5544	35.5
Zeonex E48R	1.5431	1.5333	1.5309	1.5284	1.5256	1.5231	1.5204	56.5

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Optorez 1330	1.5219	1.5119	1.5094	1.5075	1.5054	1.5026	1.4984	52.0
CTE Richardson	1.6023	1.5844	1.5802	1.5760	1.5712	1.5662	1.5615	32.8
S (low styrene)	1.5321	1.5209	1.5179	1.5142	1.5122	1.5091	1.5062	44.9
Bayer	1.6121	1.5905	1.5857	1.5814	1.5765	1.5711	1.5661	30.0
Cellulose	1.4804	1.4728	1.4706	1.4687	1.4663	1.4634	1.4608	54.1
Polyacrylate	1.5065	1.4961	1.4941	1.4924	1.4905	1.4885	1.4855	63.3
Polycarbonate	1.5971	1.5768	1.5721	1.5685	1.5645	1.5601	1.5546	28.9

2.3. Goniometric laser measurements

Laser measurements of bulk polymer samples can also be accomplished applying the goniometric method described in 2.2. The illuminating module in this case consists of a laser and expanding beam collimator with a pinhole. The experimental set-up is illustrated in Fig. 1. A conventional 1 mW He-Ne laser has been used as a light source. Results at measuring temperature of 20 °C for some of the studied OPs at laser emission wavelength λ = 632.8 nm are also presented in Table 1. Comparison among obtained results for bulk samples and thin polymer films, prepared from the same material, is possible.

3. REFRACTIVE INDEX MEASUREMENTS OF THIN POLYMER FILMS

Investigation of thin polymer films is also of great interest for production of optical sensors, displays, fibers and waveguides, etc., (Tolley 2003, Terui & Ando 2005). However, refractometric and dispersive properties of films differ in comparison with bulk plastics, as established in our previous report (Sultanova, Kasarova & Nikolov 2011). Those differences depend on the type of studied polymer as well as on the film parameters.

We have examined optical properties of several types of OPs, produced by ECC, which were deposited as thin films on glass substrate from solutions. Preparation of samples was as follows. A proper solvent for each type of polymer material has been chosen. Pellets of polyester, polyarylate, polyacrylate, and cellulose were dissolved in chloroform and two types of copolyesters – in 1,1,2,2-tetrachloroethane. Solutions of the first four materials were prepared with concentration of 10 wt% while the concentration of the copolyesters' solutions was 1 wt%.

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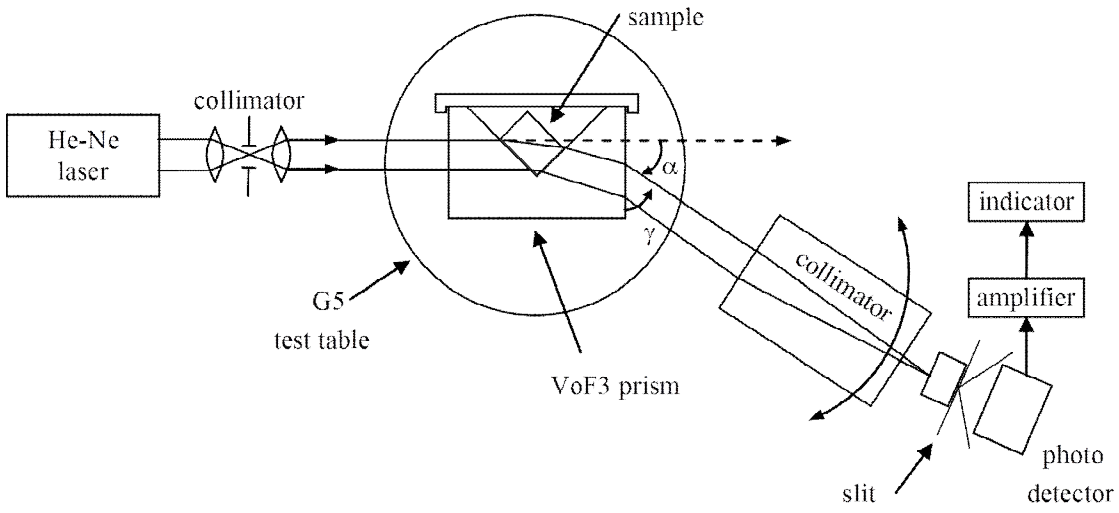

Fig. 1. Goniometric set-up with laser illumination for refractive index measurements of OPs.

Thin polymer films (TPFs) with different thickness *d* were obtained by casting a certain amount of the solution on the glass substrate. All of the studied plastics, except for the cellulose layers, were deposited on a heavy TF4 glass plate. A TK21 glass was used for the low refractive cellulose material. The samples were dried at temperature of 20 °C for 48 hours and then were heated up to 60 °C during 6 hours to evaporate the rest of the solvent. The prepared TPFs were preserved in a desiccator. A digital micrometer (Mitutoyo Corporation) was used for measuring *d* with accuracy of ± 1 μm. A matching liquid was applied to ensure the optical contact. We used methylene iodide, with a refractive index n_{633} =1.732 for the high refractive polymers, and microscopic immersion oil, with n_d = 1.52, for the polyester, polyacrylate, and cellulose materials. The measurements were carried out at room temperature of 24 °C.

Two modifications of a laser microrefractometer (LMR) were assembled to obtain refractive indices. In both cases the measuring principle is based on the critical angle determination by means of the diffraction pattern disappearance (Sainov 1991). The experimental optical schemes of the two LMRs differ only in the illumination block.

3.1. Three-wavelength microrefractometer

The principle scheme of the experimental set-up of the three-wavelength LMR is presented in Figure 2. Three lasers are used to illuminate the examined sample 6, namely, a He-Ne laser 1, and two laser diodes 2, emitting at 632.8 nm, 532 nm, and 790 nm, respectively. The three beams are collected by the two splitters 3 to form a common beam illuminating the entrance surface of the prism 5. Measured sample is positioned between the prism and a chromium diffraction grating 7 with a 40 μm period and 0.8 μm depth of the grooves. At small angles of incidence, diffraction orders are observed in reflection on the screen 8. When the angle of incidence reaches the critical angle of the material, the diffraction pattern disappears.

The critical angle φ_c is measured by rotation of the goniometric table 5 ("Microcontrolle" rotary goniometric stage with 1 arcmin resolution). Refractive index of studied polymer is calculated by the expression:

$$n_\lambda = N_\lambda \sin\left[A \pm \sin^{-1}\left(\frac{\sin\varphi_c}{N}\right)\right], \tag{2}$$

where $A = 65^o$ is the vertex angle of the prism and N_λ is the prism refractive index at the illumination wavelength ($N_{532} = 1.7490$, $N_{632.8} = 1.7347$ and $N_{790} = 1.7230$). The sign in the square brackets of Eq. (2) depends on the rotation direction of the table. Some of the obtained results for the polyarylate, polycarbonate, and two types of copolyester films are included in Table 2.

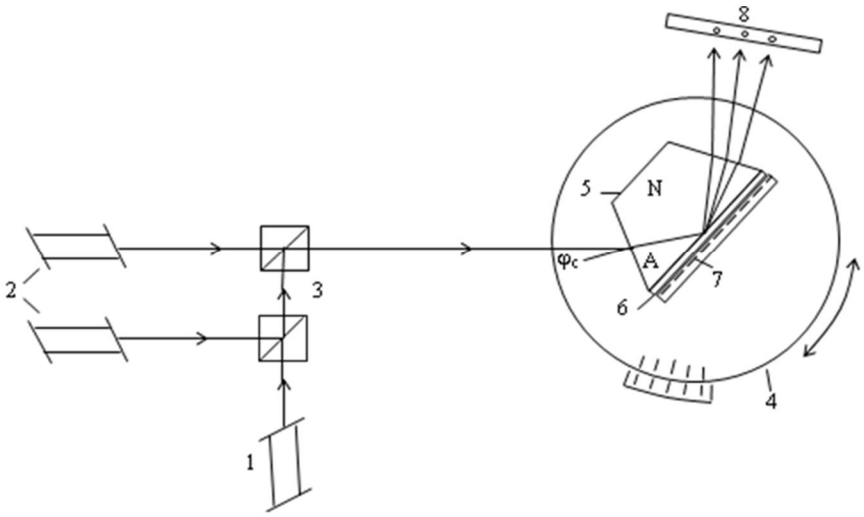

Fig. 2. A three-wavelength LMR.

Comparison among measured indices is possible at 632.8 nm. As it can be seen from Table 1 and 2, refraction of bulk PC material is lower than the ECC polycarbonate film and difference between values in second decimal place is noticed. Opposite relation is observed for the ECC polyacrylate volume sample and thin polymer layer, which is additionally measured by the four-wavelength LMR. Refractive indices of the cellulose bulk specimen and film are similar and values differ in the third decimal place. These results are in confirmation that TPFs exhibit specific refractive properties than thick polymer bodies. In case of bulk samples, volume refractive index is measured, while for TPFs, a local value of the index is registered.

3.2. Four-wavelength microrefractometer

To collect more extensive refractometric data of studied polymers, a four-wavelength LMR was also assembled according to the proposed scheme given in (Vlaeva et al. 2009). The set-up is illustrated in Figure 3, where 1 is the power supply and 2 is the optical head containing four laser diodes with emission wavelengths 406, 656, 910, and 1320 nm, respectively. Each laser diode is carefully adjusted in the vertical and horizontal plane to ensure beam passing through the two diaphragms 3, which are

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separated at a distance of 250 mm, and have an equal diameter of 2 mm. An infrared beam-finder card, model IRC32R (Electrophysics), with peak emission at 655 nm and spectral range 0.8 ÷ 1.7 μm, was used to visualize the diffraction image in the infrared spectral region. The measuring principle and procedure are identical to the described in 3.1. Calculation of refractive indices is carried out also by means of Eq. 2, taking in consideration values of N_λ of the prism at the illumination wavelengths (Russian GOST Standard 1980). Some of the obtained results are included in Table 2. Additional measurements with laser diodes emitting at 532 and 632.8 nm are also accomplished.

Table 2. Measuring results of TPFs.

TPF	*d* (μm)	Wavelength (nm)							ν_d
		406	532	632.8	656	790	910	1320	
Polyarylate	26	-	1.618	1.605	-	1.596	-	-	-
Polycarbonate	35	-	1.599	1.595	-	1.591	-	-	-
Copolyester A	6	-	1.537	1.525	-	1.514	-	-	-
Copolyester B	33	-	1.647	1.632	-	1.619	-	-	-
Polyacrylate	6	1.501	1.490	1.485	1.484		1.478	1.476	55.2
Cellulose	9	1.493	1.473	1.467	1.466		1.460	1.457	40.9
Polyester	40	1.513	1.502	1.496	1.495		1.489	1.486	53.8

A more detailed comparison among refractive characteristics of bulk polymer samples (Table 1) and TPFs (Table 2) is accomplished. Abbe numbers ν_d of studied films are determined on base of Sellmeier's and Cauchy-Schott dispersion approximations (Sultanova, Nikolov & Ivanov 2003, Kasarova et al. 2007) and refractive indices n_d, n_F and n_C are calculated. Obtained ν_d values for the materials, measured only by the four-wavelength LMR, are also presented in Table 2, since the three-wavelength LMR results are not sufficient for dispersion analysis. Estimated ν_d show that the polyacrylate and cellulose films have lower magnitudes of Abbe numbers in comparison with the bulk samples and therefore – higher dispersion. As it is well known, the variation of the refractive index with respect to the wavelength is connected with the molecular polarisability according to the classical electromagnetic theory. However, the effective electric field acting on a molecule is not the same in the volume of the substance and its surface boundary. Therefore, the dispersion properties in both cases should be different.

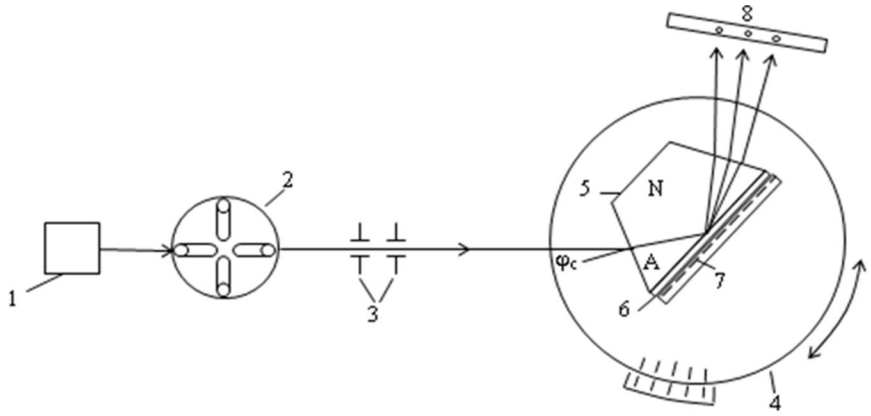


Fig. 3. Scheme of the four-wavelength LMR.

4. METROLOGICAL ANALISYS

Metrological analysis of the applied measuring methods has been carried out. We have investigated from three to five bulk polymer samples of each plastic material and the final refractive index was averaged for every selected OP. The PR2 instrument and the G5 goniometric set-up assembled with the VoF3 prism have been calibrated using a standard sodium spectral lamp and the Refractive Index Standard No 7.17 made from Sovirel BCD C 23-57 Optical French Glass (n_D=1.62270 at 20°C). A systematic error of $+5\times10^{-5}$ was established for the PR2 refractometer during the calibration test. This constant deviation value has been subtracted from the measured results and obtained refractometric data is presented in Table 1.

The metrological analysis is completed in accordance with the terminology in (The National Institute of Standards and Technology 2013). Uncertainty u_A of the results is defined as being from type A for the influence of random factors on the measuring process. Uncertainty u_B comprises instrumental errors and additional systematic deviations. The PR2 refractometer is a precise instrument with an accuracy of $\pm2\times10^{-5}$ which is the u_B uncertainty. Random errors, influenced by measuring conditions and birefringence, are also considered. The moulding process, during sample preparation, may introduce inhomogeneity, caused by internal stresses developed in the involved temperature cycles. Bulk plastics retain residual stresses even after annealing and in this way birefringence arises. Therefore, all examined samples have been checked for internal stresses in advance with the aid of a Russian polariscope PKS-125 and specimens of poor quality with refractive index difference greater than 3×10^{-4} were rejected. Standard deviation u_A has been calculated on base of five measured samples of the examined bulk material. Maximal value of $\pm5\times10^{-5}$ was obtained at the g-line for the Optorez polymer. Combined standard uncertainty u_C of our results is calculated by formula (The National Institute of Standards and Technology 2013):

$$u_C = \sqrt{u_A^2 + u_B^2} \ , \tag{3}$$

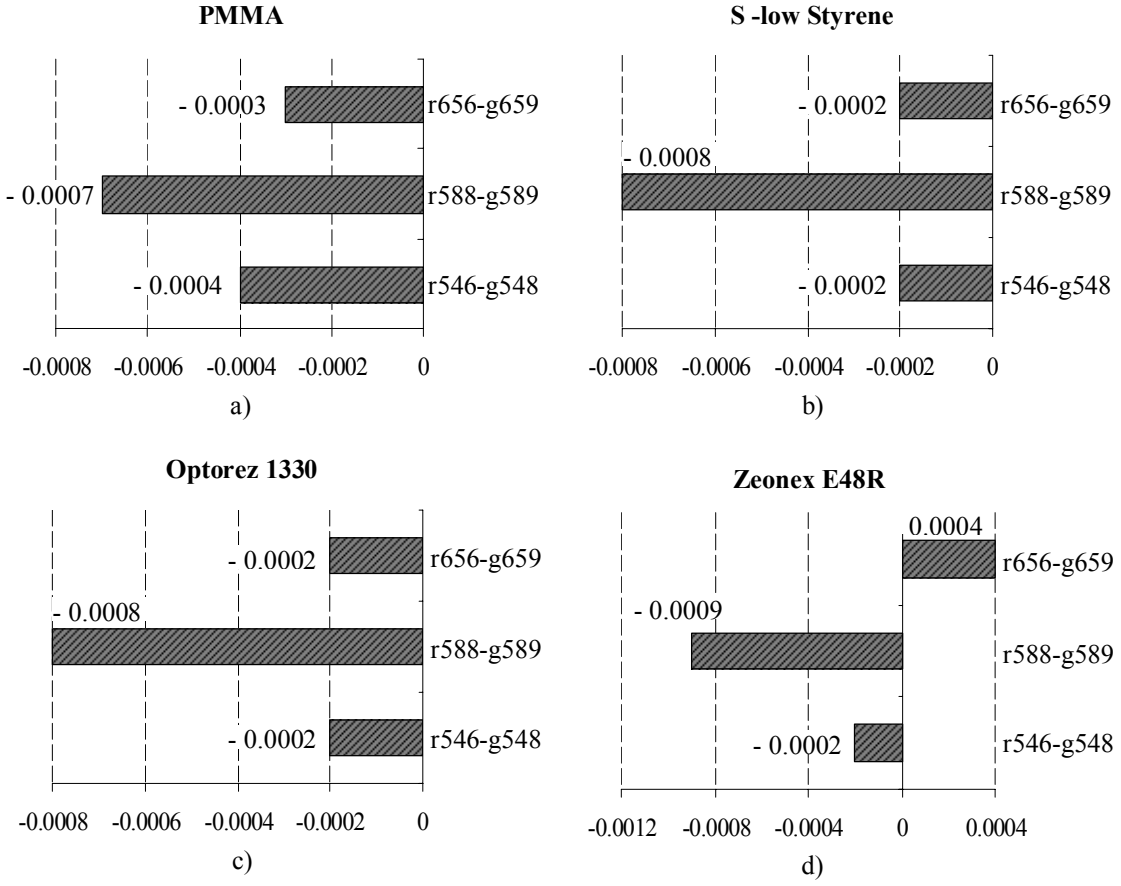
and the value of $\pm 5.4\times10^{-5}$ is estimated for the PR2 measured indices. Experimental data presented in Table 1 is at measuring temperature of 20 °C. It should be, however, underlined that OPs exhibit low thermal stability and this fact has to be carefully considered by the designers. Conclusions on base of our investigations on influence of temperature on refractive and dispersive characteristics of OPs are published in (Sultanova, Kasarova & Nikolov 2013).

The results of n_λ, obtained by the PR2 instrument and the goniometric set-up, have been compared. We have chosen three wavelength intervals in which spectral lines of the PR2 refractometer (r) correspond to the wavelengths of the interference filters (g) used in the goniometric scheme, namely, r546-g548nm, r588-g589nm and r656-g659nm. The results of the comparative analysis for four materials, which show greatest deviations among all studied polymers, are shown in Figure 4. As it can be seen the differences between the refractometric and goniometric experimental data vary for the examined OPs. In most cases the values of n_λ, measured with the PR2 refractometer, are lower than n_λ, obtained by the goniometric set-up. Maximal deviations are observed at r588-g589nm: -0.0007 for PMMA (Fig. 4a), -0.0008 for S-low Styrene and Optorez 1330 (Fig. 4b,c), and -0.0009 for Zeonex E48R (Fig. 4d). These results at the d-line can be explained by the quality of the applied interference filter and, in addition, the examined S-low Styrene, Optorez 1330, and Zeonex E48R plates are with smallest thickness among all measured OPs. Therefore, the deviated beam in these samples gives poorer signal. We found also some positive differences of $0.0003 \div 0.0004$ between refractometric and goniometric results obtained for SAN, PC, PS, etc., (Sultanova, Nikolov & Ivanov 2003). Nonlinear dependence of the established deviations with the wavelength is noticed. In all cases, however, the differences between experimental data received by both methods do not exceed the value of ± 0.0009, i.e., accuracy better than $\pm\ 1\times10^{-3}$ of n_λ measuring is obtainable through the proposed goniometric set-up.

Laser measurements of polymer bulk samples, which are carried out by means of the goniometric set-up, reveal maximal combined uncertainty of $u_C = 3.65\times10^{-4}$.

Metrological analysis of the results obtained by the laser microrefractometric method, described in 3.1 and 3.2, is also accomplished. We have used standard liquids as distilled water, ethanol and methanol for test measurements of the three-wavelength LMR. Established values for the distilled water were compared with the refractive data given in (Hale & Querry 1973) for a wide range of wavelengths. The refractive indices of water, ethanol and methanol at $\lambda = 632.8$ nm have been reported in (Moreels & Finsy 1984, Makdisi, Zaidi & Bhatia 1989). A maximal difference of $\pm1\times10^{-3}$ between our measured results and published data is observed.

Fig. 4. Comparison between PR2 instrument and goniometric set-up results.



According to formula (2) the standard uncertainty u_B for measuring film indices by both LMRs can be estimated as follows:

$$u_B = \sqrt{\left(\frac{\partial n}{\partial N_\lambda}\right)^2 u^2_{B,N_\lambda} + \left(\frac{\partial n}{\partial A}\right)^2 u^2_{B,A} + \left(\frac{\partial n}{\partial \varphi_c}\right)^2 u^2_{B,\varphi_c}}, \quad (4)$$

where u_{B,N_λ}, $u_{B,A}$ and u_{B,φ_c} are the uncertainties connected with the determination of N_λ, A and φ_c, respectively. It was found, that the last term in Eq. (4) is leading and the magnitude of u_B depends mainly on the accuracy of the goniometric table. We used a stage with 1-arcmin angular scale resolution. Estimating the partial derivative of n with respect to φ_c for small critical angles, a value of $u_B = \pm 2\times10^{-4}$ was obtained. The influence of temperature fluctuations on the results is negligible because of the short measuring time. The parallactic error during monitoring of the φ_c results on the vernier scale can be evaluated by calculation of the standard deviation. We have carried out series of three to six measurements of φ_c, for each of the examined standard liquid, at defined wavelength and a maximal magnitude of $u_{A,\varphi_c} = \pm 4\times10^{-5}$ was estimated for the obtained values at 790 nm, because of the eye's reduced sensitivity in the NIR area. Combined standard uncertainty of our results is calculated by formula (3) and value of $u_C = \pm 2\times10^{-4}$ is evaluated for standard liquids. Measurements

accomplished by both LMRs exhibit equal uncertainty u_C, since they differ only in the illumination wavelength of the applied lasers.

In case of microrefractometric measurements of TPFs, the accuracy is less, mainly because of the extra noise introduced by the multiple surface reflections in the film and the glass substrate. Some light scattering in the polymer medium also occurs. Additional refractive index fluctuations are possible due to local surface tension forces at different points of the emulsions. Several measurements of each polymer film were completed and standard deviation was estimated with maximal value of $u_A = \pm 2\times10^{-3}$.

5. SUMMARY AND DISCUSSION

Different OPs have been examined applying several measuring techniques and detailed metrological analysis has been accomplished. Bulk samples have been measured by means of the PR2 refractometer as well as on the proposed goniometric set-up (Fig. 1) in the VIS region. Refractive indices of some of the polymers are presented in Table 1. Comparison among results shows in both cases accuracy better than $\pm\ 1\times10^{-3}$ (Fig. 4). Measurements in the NIR area with the goniometric set-up have been also carried out. Presented refractive data is valuable for designers of contemporary optical devices. For this reason Abbe numbers in Table 1 are also included to illustrate dispersion properties in VIS spectrum of polymers. In NIR region variation of the refractive index with wavelength is negligible. Overall, our measurements show that OPs have a restricted range of index values, greater dispersion in VIS light and may be less dispersive in NIR area in comparison to some optical glass types.

Additional laser illumination in the goniometric set-up was applied to increase the accuracy of the obtained results and maximal combined uncertainty of $u_C = 3.65\times10^{-4}$ was achieved.

Refractive and dispersion properties of polymer films, deposited on glass substrate, have been also investigated. Two laser microrefractometers (Figs. 2 and 3) are proposed to measure indices of TPFs. Different diode lasers are applied in both cases to collect more extensive data (Table 2). The metrological analysis is accomplished with standard liquids and the combined standard uncertainty of our results was established to be $u_C = \pm\ 2\times10^{-4}$. Measurements of TPFs reveal greater diversion among obtained indices because of film non-uniformity and local surface tension values. Maximal standard deviation $u_A = \pm2\times10^{-3}$ was estimated. A comparison between refractive properties of bulk polymers and TPFs is carried out at 632.8 nm. Indices for both forms of one and the same polymer differ. A common tendency is not established. TPFs may have higher or lower refraction than bulk samples, since local index value is measured by the LMRs while PR2 instrument and the goniometric set-up register volume indices. Abbe numbers in VIS area of studied TPFs are calculated by means of Sellmeier's and Cauchy-Schott approximations. Differences between dispersion properties of TPFs and bulk polymer bodies are noticed.

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