

PLASTIC MATERIALS FOR OPTICAL APPLICATIONS

Nina G. Sultanova and Stefka N. Kasarova

Department of Physics and Mathematics, Assen Zlatarov University, 8010 Burgas, Bulgaria

E-mail: sultanova@btu.bg

Abstract

Possible applications of polymer materials in optical systems and devices are defined mainly by their refractometric and dispersive characteristics. We have examined more than twenty types of optical plastics including basic and some new development materials. Their refractive indices at a number of wavelengths in the visible and near infrared regions have been measured. Received transmission spectra reveal normal dispersion in the considered spectral range. Two mathematical models are applied to calculate the necessary optical parameters decisive in their applications. Comparison of optical and mechanical properties of the investigated plastics and some of the basic optical glasses is carried out. Some dispersion curves are provided to illustrate the possibility of replacing glasses in optical devices by a number of plastics. Refractometric characteristics of polymers at laser emission wavelengths are also presented to demonstrate their usage in coherent optics.

Key words: optical plastics, refractive properties, dispersion, visible and infrared optics

1. INTRODUCTION

Plastic materials are nowadays commonly used in the design and fabrication of optical elements and devices. They have several key advantages over optical glasses including low cost and weight, high impact resistance and ability to integrate proper mechanical and optical features [1]. Polymer optical elements and systems appear in a wide spectrum of industrial, medical, scientific, military and consumer applications. Ophthalmic optics, surgical instruments, blood analyzers, lens arrays, laser scanning systems, laser-guided weapons, identification and tracking devices, CD and DVD players are just a few examples of the creative use of optical plastics [2, 3]. Recently there has been considerable interest in the development of polymer optical fibers. They have greater advantages over glass fibers and are used in wider range of applications. It seems that optical plastics (OPs) can be both a low-cost alternative to glass and an option that provides more degrees of freedom for product and optical design. Optical plastics are presently also applied in high quality optics. Typical applications include imaging lenses, collimators, laser systems and devices. Great economies are possible through usage polymers for reproducing aspheric and other complex geometric surfaces, which are costly to produce in glass. It also refers to the production of optical elements with small dimensions. One of the most important application are the night-vision instruments as goggles, head-mounted displays, security systems lenses to detect the infrared rays of oncoming heat radiation bodies.

Optical plastics however present several challenges to the designers, including thermal effects, stress birefringence and a limited range of refractive index values. Developing the technological processes and using some new OPs overcome these problems. Today's plastics allow for higher transmittance from the ultraviolet to the infrared region, their thermal differential index of refraction coefficient has been lowered and involving component optical moulders decreases the birefringence effects. Although optical glass catalogs offer a wide range of materials, plastics nowadays are an excellent alternative to glass and their usage continues to grow in popularity.

The principal optical plastics are polymethyl methacrylate (PMMA), polystyrene (PS), polycarbonate (PC), methyl methacrylate styrene copolymer (NAS), styrene acrylonitrile (SAN), and methylpentene (TPX). Chemical companies produce various trade-marks of OPs as NAS-21 Novacor, CTE-Richardson, Zeonex, Optorez, Bayer, etc. Knowledge of their optical and mechanical properties is essential for successful application of the OPs. We have investigated refractometric and dispersion characteristics of a number of plastic materials, including the principal and some new development materials produced by the USA Eastman Chemical Company [4, 5, 6]. In this paper we compare the received results to the data of some optical glasses and consider the possibility of replacing glass components by proper plastics.

2. MEASURING THE INDICES OF REFRACTION

2.1. Measuring in the visible region

We have utilized the measuring method described in details in our paper [4]. The OPs' indices of refraction were measured with the aid of the V-type SF3 glass prism (VoF3 prism) of Carl Zeiss Jena Pulfrich-Refractometer PR2. The standard total internal reflection prism is not suitable in case of plastic samples, since they should be prepared as thick cubes with well polished surfaces and furthermore this prism doesn't avoid evaporating of the water matching liquids. The PR2 instrument is equipped with three spectral lamps for the visible (VIS) region: a mercury source with a green e-line 546.07 nm and a blue g-line 435.83 nm, a helium source for the yellow d-line 587.56 nm and red r-line 706.52 nm, and a hydrogen source for the blue F-line 486.13 nm and red C-line 656.27 nm. The VoF3 prism is produced as a glass block assembled into a massive metal body with thermostatic housing. We have produced samples of the examined OP materials having two fairly well polished, mutually perpendicular surfaces to obtain good refractometric data. The examined specimens were prepared as injection moulded plates with thickness varying from 2.5 to 5.5 mm. The plastic samples are positioned in the covered V-type VoF3 prism which is firmly fixed on the PR2 instrument. Measuring temperature of 20°C was maintained and temperature regulation was possible with stability of 0.2°C. An immersion emulsion with a proper refractive index is required to ensure the optical contact during the measurements. The alpha-bromonaphthalene is one of the most popular contacting liquids with refractive index of 1.66 but it attacks the surfaces of plastic samples. Therefore, a saturated aqueous solution of zinc chloride ($n_e = 1.51$) and silicon oil ($n_d = 1.56$) for low refractive plastic samples as PMMA, and a saturated water solution of potassium-mercuric-iodide with $n_e = 1.73$ for higher refractive PS, PC, etc. have been chosen.

2.2. Goniometric set-up for measuring in the visible and near infrared region

Additional goniometric set-up (Fig. 1) with the VoF3 refractometric prism, white lighting module with interference filters (IFs) and a photo detector device was applied for measuring in the entire VIS and near infrared (NIR) regions.

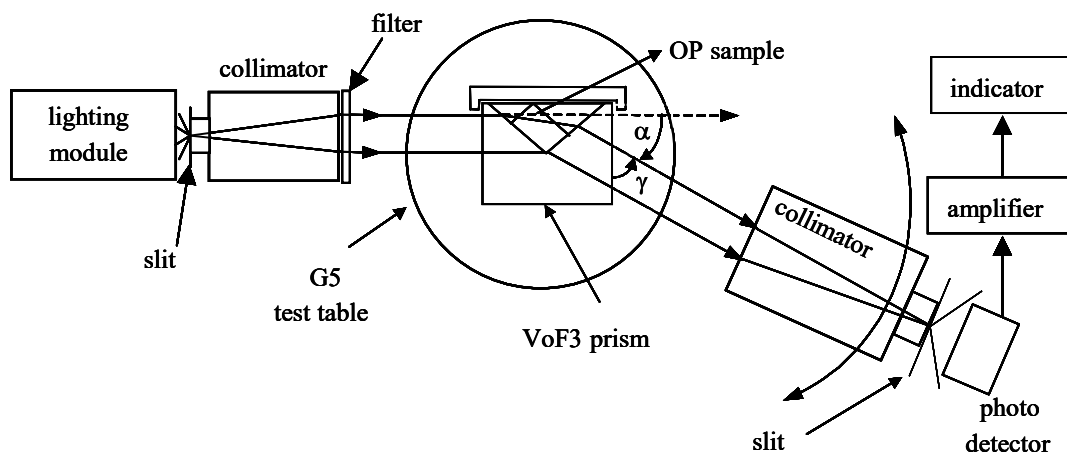


Fig. 1. Experimental set-up for measuring OP's refractive indices

A G5-LOMO goniometer with an accuracy of one arc second was used with the VoF3 prism-block, positioned on the G5 test table. The examined sample is placed and covered into the VoF3 prism. The collimated beam from the lighter falls perpendicularly to the entrance surface of the prism. The photo detector device was assembled with the aid of a plane silicon diode, operating amplifier and indicator. The lighting module consists of a 250W halogen lamp and a condenser system. A set of metal narrow band IFs, made by Carl Zeiss (Jena) was applied, namely IF 546, IF 589, IF 656, IF 700 for the VIS region, and IF 750, IF 800, IF 825, IF 875, IF 1025 – for the NIR region. The IFs in VIS region have been used for comparison between the obtained results measured with the PR2 refractometer and the G5 goniometer set-up. The right-hand collimator with the attached photo detector determines the measuring angle α (see Fig. 1). The angle of deviation γ is formed by the sample located into the V-shaped prism. The refractive index n_λ of the examined polymer is calculated as follows:

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

where N_λ is the refractive index of the VoF3 prism, γ is the calculated angle of the deviated beam, and α is the measured angle on the G5 set-up. The metrological tests [4] pointed out that our measurements of the OPs' indices guarantee the accuracy of ± 0.001 . Laser measurements [6] with a HeNe laser at $\lambda=632.8$ nm as a lighting module in Fig.1 have been also accomplished.

2.3. Measured refractive indices

Some of the experimental results are included in Table 1. We present the measured refractive indices for some of the principal, several trade marks of OPs and development materials of the American Eastman Chemical Company (ECC). First three columns refer to the indices measured by means of the PR2 instrument and the other three present the results received on the goniometric set-up. On the base of the obtained data analysis of refractive and dispersion properties has been accomplished.

Table 1. Measured refractive indices and Abbe numbers of OPs

OP material		Wavelength (nm)						Abbe number	
		435.8	486.1	587.6	703	833	1052	V _d	V ₈₇₉
Principal OPs	PMMA	1.5025	1.4973	1.4914	1.4863	1.4839	1.4813	59.2	96.7
	PS	1.6171	1.6056	1.5917	1.5821	1.5767	1.5718	29.1	54.6
	PC	1.6117	1.5994	1.5849	1.5749	1.5695	1.5645	30.5	56.4
	SAN	1.5882	1.5783	1.5667	1.5579	1.5536	1.5496	35.4	66.6
Trade marks of OPs	CTE Richardson	1.6023	1.5927	1.5802	1.5712	1.5662	1.5615	32.8	58.3
	NAS-21	1.5933	1.5835	1.5714	1.5643	1.5582	1.5544	35.5	56.3
	S (low styrene)	1.5321	1.5261	1.5179	1.5122	1.5091	1.5062	44.9	79.4
	Optorez 1330	1.5219	1.5163	1.5094	1.5054	1.5026	1.4984	52.0	71.7
	Zeonex E48R	1.5431	1.5376	1.5309	1.5256	1.5231	1.5204	56.5	100.5
	Bayer	1.6121	1.5998	1.5857	1.5765	1.5711	1.5661	30.0	54.3
ECC samples	Cellulose	1.4804	1.4765	1.4706	1.4663	1.4634	1.4608	54.1	84.1
	Polyacrylate	1.5065	1.4995	1.4941	1.4905	1.4885	1.4855	63.3	97.6
	Styrene	1.5337	1.5273	1.5189	1.5133	1.5097	1.5067	42.9	77.1
	Polycarbonate	1.5971	1.5867	1.5721	1.5645	1.5601	1.5546	31.19	54.63
	Polystyrene	1.6154	1.6038	1.5918	1.5819	1.5763	1.5715	33.40	56.41
	Acrylic	1.5023	1.4977	1.4917	1.4879	1.4854	1.4829	57.8	96.9
	EBM Copolyester	1.5856	1.5741	1.5606	1.5536	1.5476	1.5443	33.52	60.01
	S Copolyester	1.5932	1.5816	1.5669	1.5603	1.5542	1.5511	31.92	60.06

3. ANALYSIS OF OPTICAL PLASTICS' DISPERSION

3.1. Transmittance spectra

Evidence of normal dispersion of OPs in the VIS and NIR regions is obtained by measuring the transmittance spectra of the examined materials. We used a UV-VIS-NIR spectrophotometer Varian Carry 5E and transmittances of thin polymer films as Polycarbonate, Polyarylate, Polyacrylate, Cellulose, Polyester and Copolyester were measured in the spectral range from 400 nm to 2500 nm with an accuracy of 0.2 %. All received spectra confirm normal dispersion in the considered spectral range. In Fig. 2 transmittance spectrum of a Polycarbonate thin film is presented. As it can be seen there is a weak absorption band at 1670 nm and more evident absorption is observed above 2000 nm.

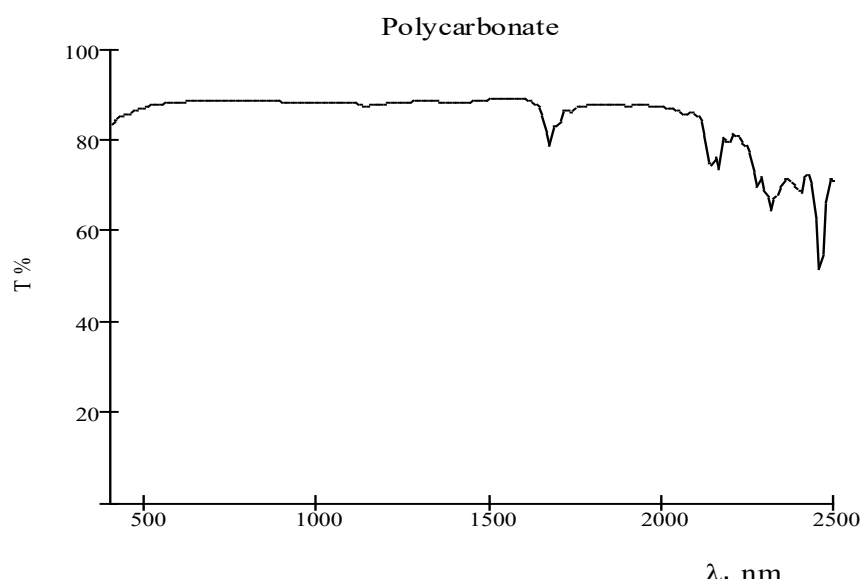


Fig. 2. Transmission spectrum of a 35μm thick PC film

3.2. Mathematical models evaluating optical plastics' dispersion

There are several approximating dispersive equations in literature as Hezberger's, Hartmann's, Cauchy's and Sellmeier's formulae [4]. We have applied the modified Cauchy-Schott formula [4, 5] involving six dispersion coefficients which assures calculation accuracy better than ± 0.0001 . Usually, three terms in the Sellmeier's approximation are used to ensure sufficient precision over the wavelength range from the ultraviolet to the infrared area [4, 7]. On the base of the measured refractive index data the dispersion coefficients of the investigated optical materials can be determined by the expressions:

$$n_{\lambda}^2 = A_1 + A_2\lambda^2 + \frac{A_3}{\lambda^2} + \frac{A_4}{\lambda^4} + \frac{A_5}{\lambda^6} + \frac{A_6}{\lambda^8}, \quad (2)$$

$$n_{\lambda}^2 = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}, \quad (3)$$

where $A_1, \dots, A_6$ are the Cauchy's coefficients, and B_i, C_i ($i = 1 \dots 3$) are the Sellmeier's constants, related to the oscillators' strength and resonance wavelengths. We have realized the program OptiColor [5] on the base of Eq. (2) that allows us to obtain the dispersion coefficients of any optical material in the region of normal dispersion. The input data is six refractive indices of the examined sample at selected measuring wavelengths. The program calculates coefficients from A_1 to A_6 in Eq. (2) using a system consisting of six linear equations. Dispersion curves can be drawn too. In Fig. 3 dispersion charts of three polymer materials are presented. Refractive indices fall uniformly down with the increase of the wavelength.

We have used also the Sellmeier's formula (3) to reveal dispersion properties of bulk and thin film polymer samples. In case of input six measured indices both approximations yield similar calculation accuracy [5]. Therefore we preferred the Cauchy's linear system of equations and our program OptiColor for evaluation of dispersion properties of studied materials. Measuring of refractive indices

at laser emission wavelengths is usually possible at less than six wavelengths and then both dispersion models have been utilized, especially in case of thin film polymer materials. Comparison of the obtained results has been accomplished [5] and a maximal difference in the third decimal value has been observed.

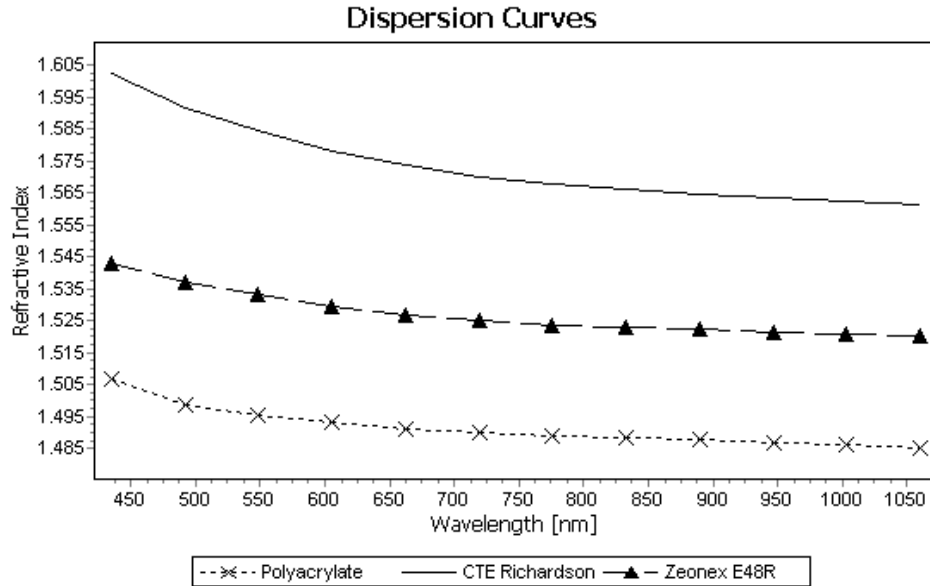


Fig. 3. Computed dispersion curves of three optical plastics

More detailed examination of the dispersion behaviour of optical materials can be accomplished by calculating the wavelength dependence of $dn/d\lambda$ in various parts of the spectrum [8]. Normalization of dispersion curves at definite wavelength e.g. 550 nm [9] for VIS and 880 nm for NIR is also useful for the comparison of optical properties.

On the base of Eq. 2 refractive indices of the polymer materials at any fixed wavelength in the region of normal dispersion can be computed. The obtained results for the examined OPs at some emission wavelengths of well-known lasing media in the VIS and NIR spectral regions are presented in Table 2.

3.3. Abbe numbers

Dispersion of optical materials is usually evaluated by their Abbe numbers. We have calculated the mean v_d and partial dispersion v_{879} in the NIR region by the following expressions:

$$v_d = \frac{n_d - 1}{n_F - n_C}, \quad (4)$$

$$v_{879} = \frac{n_{879} - 1}{n_{703} - n_{1052}}. \quad (5)$$

Here n_d , n_F and n_C are measured indices at 587.56, 486.13 and 656.27 nm in VIS and n_{703} , n_{879} , n_{1052} – corresponding values in the NIR region. Calculated Abbe numbers of some of the studied materials are presented in Table 1. Low refractive materials as Acrylics, Cellulose, low Styrene, Optorez and Zeonex have higher Abbe numbers, while OPs with refractive indices above 1.55 have magnitude of v_d less than 40. Mean dispersion defined by Eq. (4) is the USA standard for the VIS region. European

and Japanese glass catalogues present also Abbe number v_e in respect to the green mercury e -line at 546.07 nm [7].

Table 2. Calculated refractive indices of OPs at different laser emission wavelengths

OP material		Laser emission wavelength (nm)							
		405	488	532	632.8	694.3	799.3	860	1064
Principal OPs	PMMA	1.516	1.497	1.495	1.489	1.487	1.484	1.484	1.481
	PS	1.634	1.605	1.599	1.587	1.583	1.578	1.576	1.572
	PC	1.631	1.599	1.592	1.580	1.575	1.571	1.569	1.564
	SAN	1.608	1.578	1.573	1.563	1.558	1.554	1.553	1.549
Trade marks of OPs	CTE Rich.	1.612	1.592	1.587	1.576	1.571	1.567	1.566	1.562
	NAS-21	1.588	1.583	1.577	1.568	1.564	1.559	1.557	1.554
	S (low st.)	1.542	1.526	1.522	1.515	1.512	1.510	1.509	1.506
	Optorez 1330	1.531	1.516	1.513	1.507	1.505	1.503	1.502	1.498
	Zeonex E48R	1.555	1.537	1.535	1.528	1.526	1.524	1.523	1.520
	Bayer	1.623	1.599	1.593	1.582	1.578	1.572	1.570	1.566
ECP samples	Cellulose	1.484	1.476	1.474	1.469	1.467	1.464	1.463	1.461
	Polyacrylate	1.521	1.499	1.497	1.492	1.491	1.490	1.488	1.485
	Styrene	1.540	1.527	1.523	1.516	1.514	1.510	1.509	1.507
	Polycarbonate	1.602	1.586	1.579	1.568	1.565	1.561	1.559	1.554
	Polystyrene	1.640	1.604	1.598	1.587	1.582	1.577	1.576	1.571
	Acrylic	1.506	1.498	1.495	1.490	1.488	1.486	1.485	1.483
	EBM Copol.	1.585	1.574	1.566	1.558	1.554	1.549	1.547	1.544
	S Copol.	1.586	1.581	1.573	1.564	1.561	1.556	1.553	1.551

4. COMPARISON BETWEEN OPTICAL PLASTICS AND GLASSES

Possible replacement of glasses in optical components and systems should be regarded on the base of their optical and mechanical properties. We have chosen two SCHOTT optical glasses as N-BK7 and N-SK16 with similar refractive indices to the studied polymers PMMA and PS, respectively. Comparison among plastics and glasses in respect to their optical characteristics has been accomplished following the dispersion analysis in Section 3.

Dispersion curves of polymers and glasses calculated by means of our OptiColor program are presented in Fig. 4. The presented plots are smooth and monotonously decreasing in the range of normal dispersion which is in unison with the approximation, given in Eq. 2. As it can be seen, the slope of the curves for glasses is less compared to that of the polymers. Evidently dispersion of OPs is greater at the beginning of the VIS area, especially in Fig. 4b. This fact should be taken in account by the designers for better correction of chromatic aberrations of the optical elements.

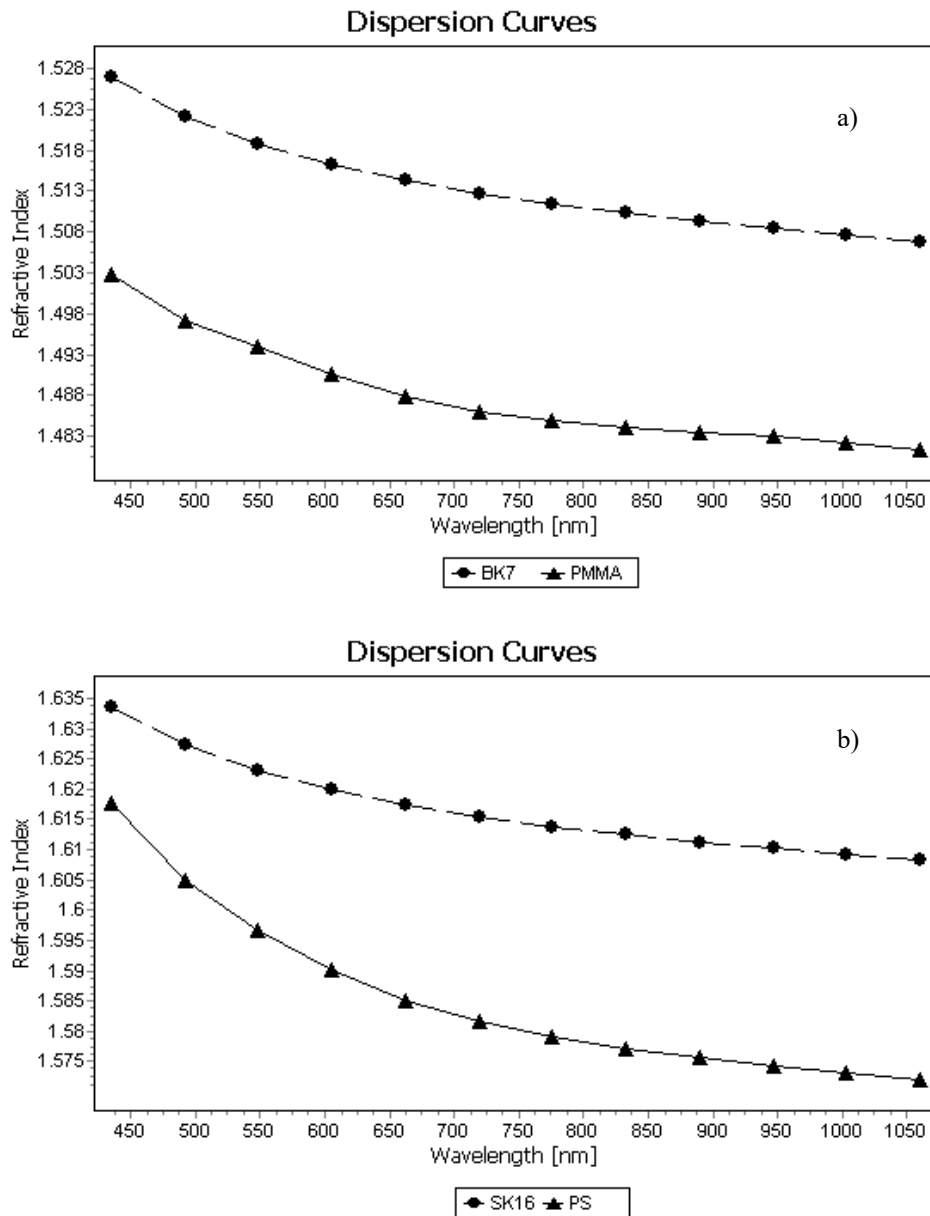


Fig. 4. Comparative dispersion curves between glasses and plastics:
a) N-BK7 glass and PMMA; b) N-SK16 glass and PS

More thorough examination of the slope of the dispersion charts is achieved by means of calculation of the wavelength dependence of $dn/d\lambda$. Nonlinear behaviour of plots for both plastics and glasses is observed. Obviously refractometric characteristics of optical materials in VIS region are decisive for their applications. Flat parts of $dn/d\lambda$ curves in NIR region make polymers well-situated for broad wavelength applications in night-vision instruments and systems.

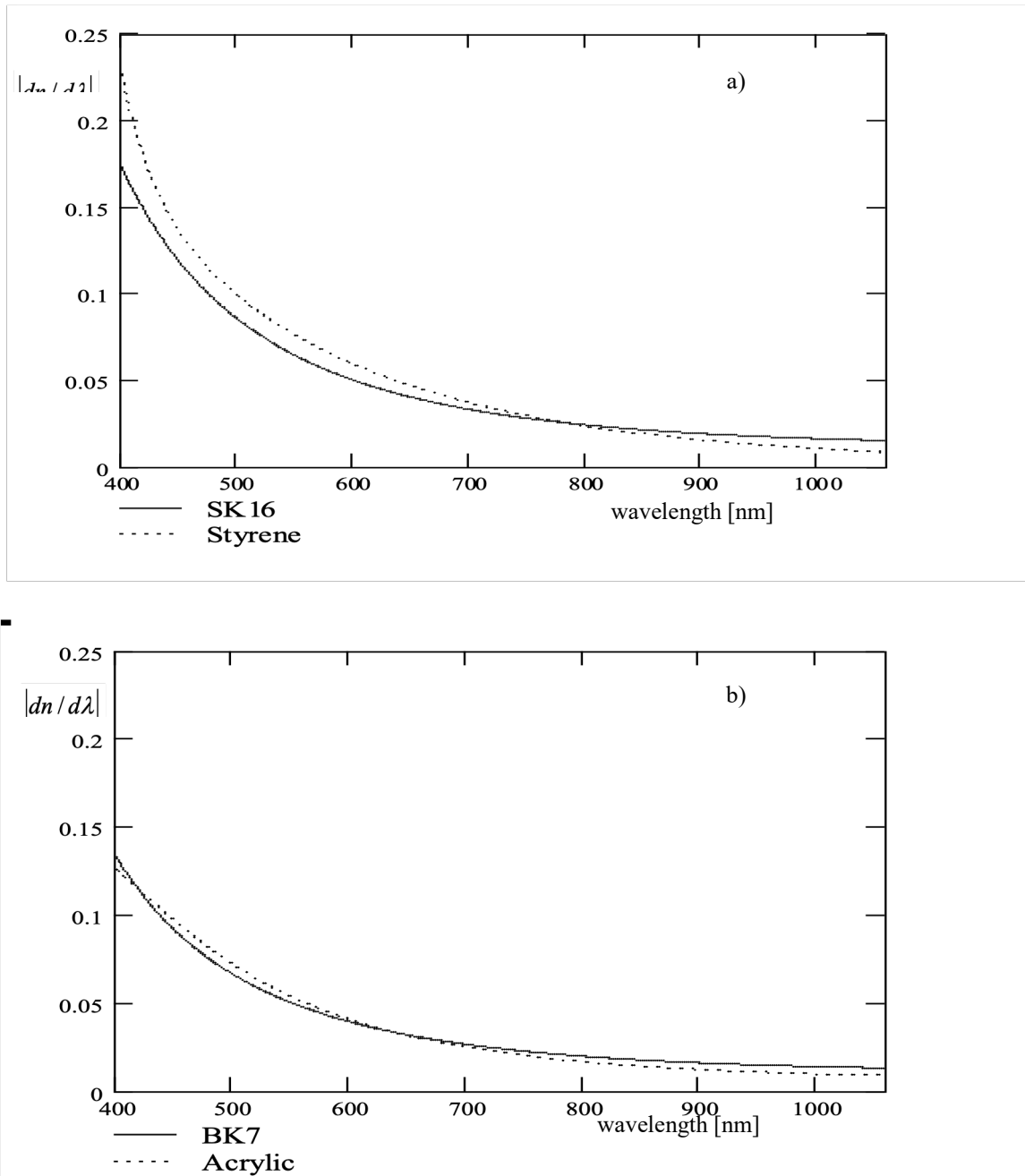


Fig. 5. Wavelength dependence $|dn/d\lambda|$ of Schott glasses compared with ECC plastics:
a) N-SK16 and Styrene; b) N-BK7 and Acrylic

A better comparison and visualization of the dispersion properties of the examined materials is achieved by presentation of the normalized curves to the refractive index value at 550 nm for VIS (Fig. 6a) and 880 nm for NIR (Fig. 6b), respectively. Though there is a considerable difference in the refractive index values of the Acrylic polymer and the N-SK16 glass, their normalized curves coincide which assumes similar dispersion properties of both materials. In case of the PS material, however,

dispersion in VIS is extremely essential. The evident flatness of charts in the NIR region confirms their lower dispersion.

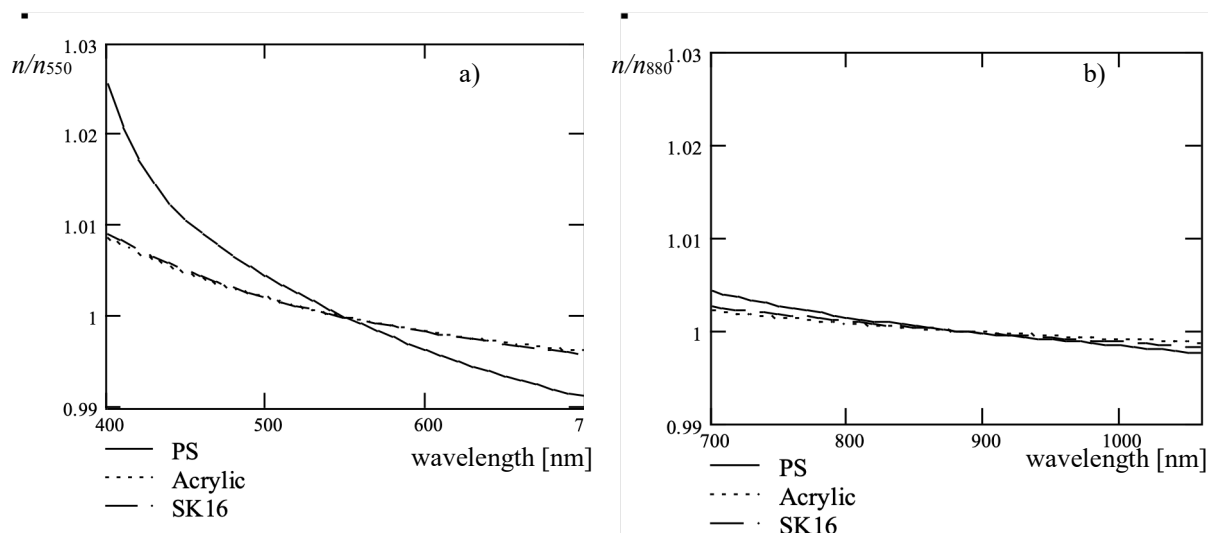


Fig. 6. Normalized dispersion curves at a) 550 nm; b) 880 nm.

Abbe numbers for mean v_d and partial dispersion v_{879} of selected materials are presented in Table 3. Materials with low refractive indices usually have low dispersion behaviour and therefore a high Abbe number. The similar dispersion properties of the N-SK16 glass and the Acrylic polymer as well as the essential dispersion of the PS material are confirmed again by their Abbe number values.

Table 3. Comparative Abbe numbers of plastics and glasses for VIS and NIR region

	Acrylic	PS	PC	Optorez 1330	N-BK7	N-SK16	N-BAK2
v_d	57.8	29.1	30.5	52.0	64.17	60.32	59.71
v_{879}	96.9	54.6	56.4	71.7	82.27	81.66	82.46

Mechanical properties of plastics and glasses are very important for their applications too. Usually, elasticity of the materials is defined by their Young's tensile modulus E . Some other characteristics as Kirchoff's shear modulus G and the Poisson ratio μ , which is interrelated with E and G are also available in the reference technical information [7, 9, 10]. The elasticity and rigidity of polymers determine their brittle strength and impact resistance and are therefore factors that influence on safety. The parameters E , G and μ are characteristic constants of the individual glass type and depend on the particular chemical composition. In case of polymers these properties are dependent not only on the specified polymer alloy and additives, but also on the processing technology [10]. Usually, extruded, cast and moulded polymer samples are distinguished. In Table 4 some physicomechanical properties of several OPs and glasses are provided. Polymers have considerably lower density ρ of the order of 2 to 4 times smaller values. This is a great advantage of plastics which guarantees less weight of the end

optical components compared to glass products. It is evident that mechanical features of plastics and glasses are quite different. In case of moulded polymer samples only the Young's moduli are given [9, 10] while for cast and extruded samples the values of G and μ are also available [10]. The values of E , G and μ in case of optical glasses, presented in Table 4, have been established and calculated by means of a double-exposure holographic interferometric technique [11] within an a 3% accuracy for the E and G moduli and $\pm 10^{-3}$ for the Poisson ratio μ . Young's modulus of elasticity of OPs is 20 to 50 times smaller than the value for glasses. For example, the PMMA polymer exhibits almost 40 times smaller values of E . Values of G and μ are presented for the acrylic Evonic Plexiglas Extruded material [10].

Thermal properties of plastics are rather different compared to glasses. Service temperature limits for OPs (60 °C to 250 °C) are substantially less than for optical glasses (400 °C to 700 °C). The thermal expansion coefficient α (Table 4) is about one order of magnitude greater than glass. For example, the linear thermal expansion of PMMA has average value of $7 \times 10^{-5} \text{ K}^{-1}$ while that for N-BK7 glass is $0.71 \times 10^{-5} \text{ K}^{-1}$. Another important parameter for optical materials is the variation of refractive index with temperature dn/dt . The temperature range from 20 to 40 °C is considered for comparison between polymers and glasses. In case of polymers dn/dt can be from 6 to 50 times greater than that of glass depending on the specific materials being compared. For acrylic, the change of refraction with temperature is approximately $-8.5 \times 10^{-5} \text{ K}^{-1}$ [12] and for N-BK7 glass, the value is $1.6 \times 10^{-5} \text{ K}^{-1}$ [7]. Therefore, designers should be aware that plastic elements do not perform well in environments where large temperature fluctuations exist and this is an important disadvantage of OPs.

Table 4. Physicomechanical properties of plastics and glasses

Material	$\rho \times 10^3 \text{ kg/m}^3$	$E \times 10^{10} \text{ Pa}$	$G \times 10^{10} \text{ Pa}$	μ	$\alpha \times 10^{-5} \text{ K}^{-1}$
PMMA	$1.17 \div 1.2^{[9]}$	$0.22 \div 0.32^{[9]}$	$0.17^{[10]}$	$0.37^{[10]}$	$5 \div 9^{[9]}$
PS	$1.04 \div 1.05^{[9]}$	$0.31 \div 0.33^{[9]}$	$0.12^{[13]}$	$0.325 \div 0.33^{[13]}$	$6 \div 8^{[9]}$
PC	$1.2^{[9]}$	$0.21^{[9]}$	-	-	$7^{[9]}$
ZeonexE48R	$1.01^{[9]}$	$0.25^{[9]}$	-	-	$6^{[9]}$
N-BK7	$2.51^{[7]}$	$8.074^{[11]}$	$3.290^{[11]}$	$0.227^{[11]}$	$0.71^{[7]}$
N-SK16	$3.58^{[7]}$	$8.025^{[11]}$	$3.169^{[11]}$	$0.266^{[11]}$	$0.63^{[7]}$

5. SUMMURY AND CONCLUSIONS

In this report refractometric and dispersion characteristics of a number of OPs are presented. Refractive indices at several wavelengths in VIS and NIR regions have been measured (Table 1). Normal dispersion of polymers is confirmed by means of the obtained transmission spectra (Fig. 2). Therefore, the Cauchy – Schott and Sellmeier approximations have been used for evaluation of dispersive properties. Dispersion coefficients, dispersion charts and Abbe numbers have been calculated (Tables 1 and 3, Fig. 3). Refractive indices of OPs at selected laser emission wavelengths are obtained (Table 2). This data could be useful in the design of coherent optical elements and devices.

Optical and some physical properties of OPs have been compared with basic SCHOTT glasses as N-BK7 and N-SK16. Comparative dispersion curves (Fig. 4) reveal similar refractive properties. The slope of the curves for glasses is less compared to that of the polymers which shows that dispersion of OPs is greater at the beginning of the VIS area. Therefore, correction of chromatic aberrations of the

plastic elements in this spectral region should be carefully considered. Comparative Abbe numbers (Table 3) of plastics and glasses for VIS and NIR region have been also calculated.

A better evaluation of dispersion properties of optical materials is obtained on the base of the wavelength dependence of $dn/d\lambda$ (Fig. 5). Normalization of dispersion curves (Fig. 6) is also applied. Greater variation of the dispersion for both plastics and glasses is observed in the VIS region while the normalized curves almost overlap in the NIR area. Though the Schott N-SK16 glass has higher refractive index values compared to the Acrylic polymer, the dispersion properties of both materials are very close (Fig. 6 and Table 3). Dispersion in the NIR range is not a limiting factor for the polymers where their normalized curves are extremely flat (Fig. 6b). This result makes OPs well suited in night-vision applications.

Some mechanical and thermal properties of OPs have been also compared with those of glasses (Table 4). OPs have much lower density. This is a significant factor in material selection depending on system requirements. The lower weight of plastic components compared to glass products allows simpler mounting mechanisms and thus reduction of the weight of the entire product is possible. Evaluation of rigidity of plastics is based on the examination of their elastic modulus. Attention should be drawn to the thermal properties of polymers which are rather restrictive. Most optical elements made of plastics do not operate in conditions that exceed the thermal limits of polymers. The thermal deviation of index of refraction should be also taken in consideration.

Overall, the variety of materials for glass optics exceeds essentially those which are currently available for plastic optics. Nevertheless, this disadvantage could be compensated by using aspherics, binaries, and diffractives, which are essentially cheaper to produce in plastics. Innovative materials and improved tooling and processing bring plastics to the forefront of consumer and high quality optics.

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