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Characteristics of Optical Polymers in the Design of Polymer and Hybrid Optical Systems*

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Abstract. Refractometric and dispersive characteristics of polymers are investigated to confirm their application in the design of optical systems. Refractive indices of different types of materials are accurately measured in the visible and near-infrared spectra and dispersive parameters are analyzed. Influence of temperature is considered. Examples of polymer and hybrid glass-polymer optical elements and devices are presented.

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1 Introduction

Polymer materials are nowadays used not only in the design of consumer but also of precise optical systems and devices [1]. Their refractometric and dispersive characteristics as well as some physical, mechanical and thermal properties are essential in the design and production of optical elements. Optical polymers (OPs) have some key advantages over glass as low cost and weight, high impact resistance and ability to integrate proper mechanical and optical features. They are clear materials that provide excellent light transmission in the visible (VIS) and near-infrared (NIR) regions [2]. Great economies are possible through usage of OPs for reproducing aspheric and other complex geometric surfaces or miniature elements, which are costly to produce in glass. If temperature in the technological processes is rigorously controlled, polymer products with birefringence as low as 10^{-5} or 10^{-6} are manufactured [3]. OPs reveal also certain disadvantages as a limited range of refractive index values, low thermal stability and scratch resistance, as well as hygroscopicity and UV or high-energy radiation destruction of the material. Some of these difficulties could be eliminated if plastic products are supplied with hard, anti-abrasion or antireflection coatings

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with anti-static and hydrophobic properties, helping to maintain the transparency of the surfaces and making them easier to clean. To overcome the sensitivity to temperature of polymers, in recent times hybrid optical elements are used to combine the advantages of optical glass and plastic materials [1,2].

We have investigated refractometric and dispersive properties of all of the principal polymers, many trade-marks and some new development materials. Different measuring techniques are used to obtain precise refractive index data of bulk polymer samples [4] as well as thin films [5] in the VIS and NIR spectra. On base of measured results dispersion coefficients and curves are calculated. Temperature dependence of refraction is investigated in the limits from 10 to 50°C and the thermo-optic coefficients of polymers are determined. Comparative refractometric and dispersive characteristics of OPs and glasses are discussed to confirm their compatibility in hybrid glass-plastic elements.

2 Refractive and Dispersive Characteristics of OPs

We have studied optical properties of the principal OPs as polymethyl methacrylate (PMMA), polystyrene (PS), polycarbonate (PC), methyl methacrylate styrene copolymer (NAS), styrene acrylonitrile (SAN) and different trade-marks as NAS-21 Novacor, CTE-Richardson, Zeonex, Optorez, Bayer. Control samples produced by the American Eastman Chemical Company (ECC) are also examined.

Proper choice of measuring technique depends on the sample shape, size and thickness. Several methods were applied to determine refractive indices n_λ of OPs at sixteen wavelengths λ from 435.8 to 1052 nm at 20°C. The classical Zeiss Pulfrich refractometer with its V-type SF3 glass prism was used to obtain refractometric data with an accuracy of $\pm 2 \times 10^{-5}$ of bulk polymer samples at five spectral lines in the VIS region. Combined standard uncertainty u_C of our results was found to be $\pm 5.4 \times 10^{-5}$ [6]. We have assembled an experimental set-up including one-arc second goniometer, a white lighting module with interference filters and a photo detector device to obtain indices of refraction in the VIS and NIR regions. A number of the polymer specimens have been measured by this goniometric set-up and a He-Ne laser at 632.8 nm as a light source. In all cases the deviation angle method is applied. Our metrological analysis shows accuracy better than $\pm 1 \times 10^{-3}$ of n_λ in the entire spectrum [4]. Laser measurements by the goniometric set-up yield $u_C = 3.65 \times 10^{-4}$ [6]. Some of the results at spectral d-, s-, t-lines with wavelengths of 587.6, 852.1, 1013.9 nm, respectively, and n_{633} are given in Table 1. The EBM copolyester is an ECC material. The SCHOTT borosilicate crown N-BK10 [7] is included to compare polymers and optical glasses.

Thin polymer films (TPFs) have been also measured and they reveal different refractive properties in comparison to bulk samples [5]. For this purpose two modifications of a laser microrefractometer have been assembled to measure refractive indices at three or four wavelengths in VIS and NIR regions. TPFs are widely used in photonic applications but also they could be deposited as a layer over glass components to obtain precise and thermally stable devices [1].

Polymers are very sensitive to temperature changes. Compared to glass, their thermal expansion coefficients are often an order of magnitude larger. However, the most important parameter for optical applications is the temperature gradient $\mathrm{d}n/\mathrm{d}T$. This quantity, known as a thermo-optic coefficient, has been estimated in the range between 10 and 50°C. For this reason refractive index measurements of polymers at varying temperature were completed at several wavelengths [2]. The thermo-optic coefficients in the limits from 20 to 50°C at the d-spectral line are included in Table 1. Their negative values contrast to the positive coefficients for most of glass types and are one or two orders of magnitude larger [7]. Dispersion properties of OPs are also influenced by temperature [2].

Table 1: Refractive and dispersive characteristics of OPs and N-BK10 glass

	PMMA	Zeonex E48R	Optorez 1330	SAN	EBM Copol.	PS	PC	N-BK10
n_d	1.4914	1.5309	1.5094	1.5667	1.5613	1.5917	1.5849	1.49782
n_{633}	1.4890	1.5284	1.5075	1.5626	1.5582	1.5872	1.5802	1.49623
n_s	1.4840	1.5228	1.5022	1.5532	1.5474	1.5762	1.5690	1.49127
n_t	1.4819	1.5209	1.4992	1.5504	1.5446	1.5726	1.5654	1.48887
$n_F - n_C$	0.0083	0.0094	0.0098	0.0160	0.0179	0.0194	0.0201	0.00744
ν_d	59.2	56.5	52.0	35.4	31.4	30.5	29.1	66.95
$n_g - n_F$	0.0052	0.0055	0.0056	0.0099	0.0114	0.0115	0.0123	0.00394
$P_{g,F}$	0.626	0.585	0.571	0.619	0.637	0.593	0.612	0.5303
$P_{d,C}$	0.289	0.287	0.296	0.275	0.251	0.283	0.279	0.3093
Δn_{NIR}	0.003	0.003	0.005	0.004	0.004	0.006	0.006	0.00375
ν_{879}	96.7	100.5	71.7	66.6	58.8	56.4	54.6	83.21
$P_{s,t}$	0.667	0.667	0.600	0.750	0.500	0.500	0.667	0.6396
$\Delta n_d/\Delta T \times 10^{-4}$, K^{-1}	-1.30	-1.26	-1.20	-1.10		-1.31	-1.00	0.034

Measured refractometric data as well as transmission curves of all studied OPs confirm their normal dispersion in the considered spectral range [2]. Therefore, we have applied the Sellmeier's and a modified Cauchy's dispersion formulae [4] to calculate dispersive characteristics of polymers. We have used the second approximation to create a program OptiColor which computes dispersion coefficients, curves, Abbe numbers and random refractive indices if the input data consists of six measured results. Dispersion curves of high and low refractive polymers are presented in Figure 1a and b, respectively. Acrylic type materials as PMMA and Optorez 1330 are compared with N-BK10 glass in Figure 1a. Though refraction of this crown is close to that of the considered polymers, the slope of its dispersion curve is lower and the corresponding Abbe number ν_d is consequently higher (Table 1). OPs are more dispersive materials than glasses in the VIS spectrum while dispersion in NIR region is substantially less. The same tendency reveals dispersion curves of higher refractive OPs, presented in

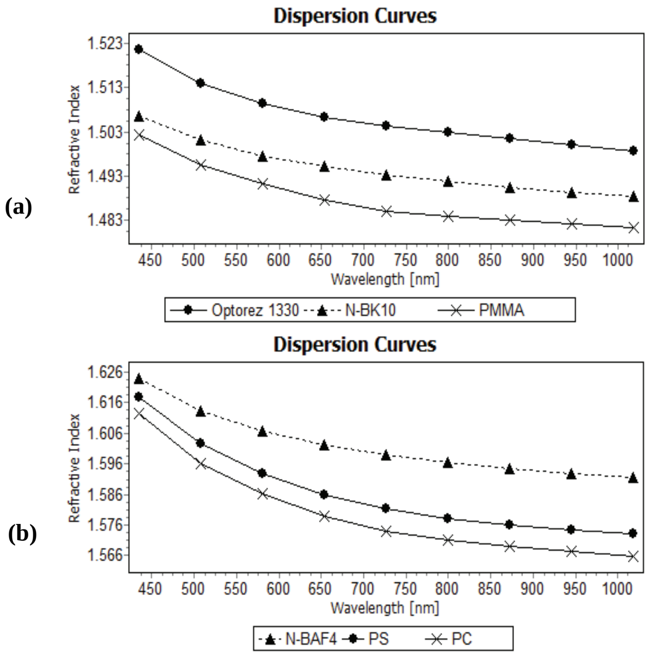

Figure 1: Dispersion curves calculated by means of OptiColor program of: (a) low; and (b) higher refractive OPs compared to glasses.

Figure 1b. Comparison to barium flint N-BAF4 with $n_d = 1.60568$, $\nu_d = 43.72$ and $\nu_{879} = 65.2$ is possible [7]. This SCHOTT glass is essentially less dispersive in the entire spectrum.

Traditionally dispersion of optical materials is presented by their Abbe numbers. In VIS spectrum ν_d and ν_e are given in glass catalogues to reveal refractive index variation with λ. To evaluate $n(\lambda)$ in the considered NIR region we define a similar Abbe number as

$$\nu_{879} = (n_{879} - 1)/(n_{703} - n_{1052}). \quad (1)$$

Additional characteristics as principal $n_F - n_C$ and partial dispersions as $n_g - n_F$ at shorter wavelengths, and $\Delta n_{NIR} = n_{804} - n_{1052}$ are calculated. Polymers in Table 1 are arranged in accordance of decreasing value of ν_d and therefore increasing principal and partial dispersions of the materials. In the design of precise optical elements relative partial dispersions $P_{x,y}$ in different spectral regions are acquired. Values of $P_{g,F}$ and $P_{d,C}$ are calculated for VIS spectrum and analogues quantity $P_{s,t}$ in the NIR region is introduced. At fixed wavelengths x and y in the VIS light $P_{x,y}$ and $P_{s,t}$ for NIR region are defined as

$$P_{x,y} = (n_x - n_y)/(n_F - n_C); \qquad P_{s,t} = (n_s - n_t)/(n_{804} - n_{1052}), \quad (2)$$

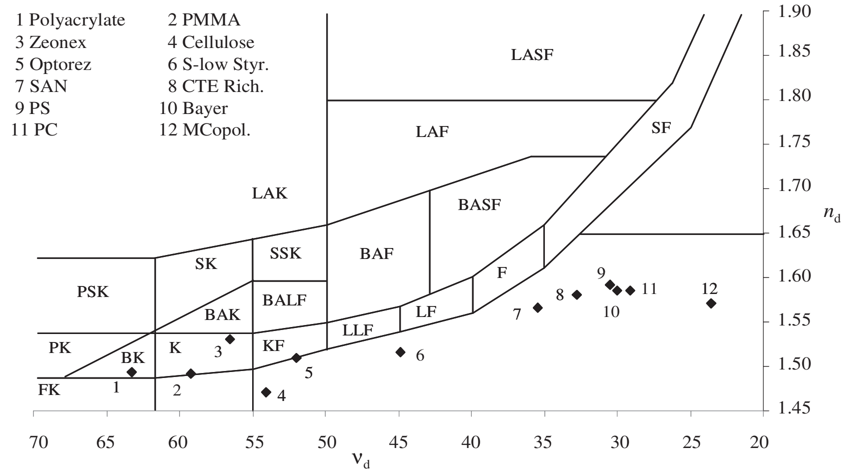

Figure 2: Abbe diagram of OPs and SCHOTT glasses.

where subscripts (F, C, d, g, s, t) express the Fraunhofer spectral lines. Calculated values are included in Table 1. As it is known, these quantities are important for chromatic correction. In the design of multiple component optical systems relative partial dispersions should be closely matched while Abbe numbers should differ substantially. As for example, in the VIS region the PMMA could be combined with the PS or PC material in an achromatic pair. The Zeonex material and PS plastic also form a suitable plastic doublet.

Our results confirm that polymers are higher dispersive materials than glasses in the VIS light. In the NIR region, however, there are some OPs as PMMA and Zeonex 1330 that are less dispersive than glasses. They have higher ν_{879} and lower Δn_{NIR} values than a typical crown glass. These plastics seem to be the most suitable materials for night vision applications. According to the values of ν_{879} and $P_{s,t}$ in the NIR spectrum (Table 1) achromatic pairs form PMMA or Zeonex with PC. The N-BK10 glass could be incorporated with PC plastic in a hybrid doublet, too.

A joint Abbe diagram of OPs and glasses is given in Figure 2. As it can be seen OPs have a rather limited range of n_d values. The polymer with a maximal value of ν_d in Table 1 is the PMMA material, which is a typical magnitude for all crown glasses as BK, K, BAK, etc. Most of the indicated polymers in Figure 2 show lower refraction than glass but higher dispersion. Glass types with low values of ν_d usually are much higher refractive materials as dense flints SF, BASF, LASF. In this sense, polymers complement available classes of optical media with lower refractive but higher dispersive materials.

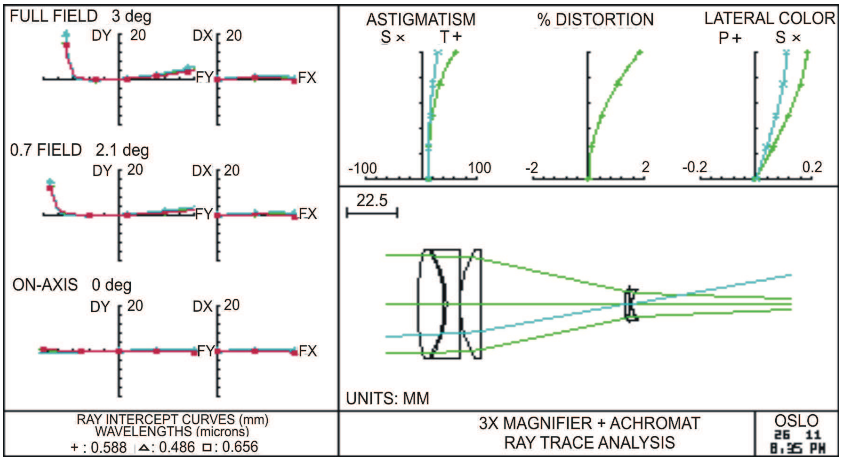

Figure 3: Optical scheme and geometrical aberrations of all-plastic magnifier and achromatic eyepiece.

3 Examples of Design of Polymer and Hybrid Optical Systems

Design of an all-plastic magnifier composed of PMMA, PS and PMMA elements and an achromat made of PMMA and PS is presented in Figure 3. The triplet is with back focal length 644.3 mm, numerical aperture NA = 0.0396 and 3× magnification. PMMA and PS plastics are incorporated for better colour image correction. Geometric aberrations are calculated by means of OSLO design software and ray intercept curves are presented at wavelengths 486, 588 and 656 nm. The optical system is compact with low weight and therefore suitable to enhance magnification of night-vision devices.

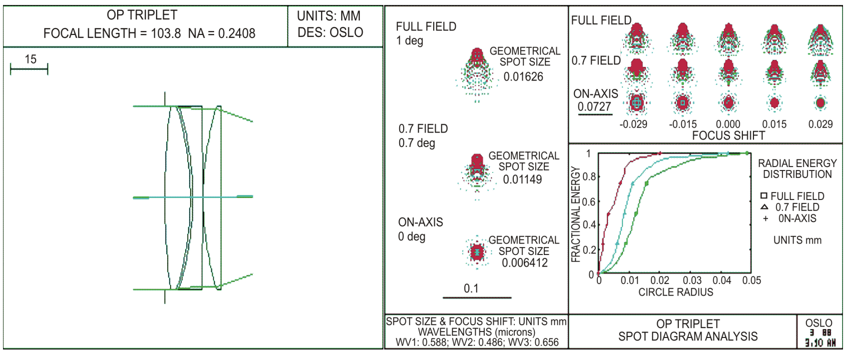

Figure 4: Optical scheme and spot diagram analysis of a hybrid triplet.

The scheme of a hybrid triplet is presented in Figure 4. The first two lenses are made of PMMA and PS while the converging lens is from N-BK10 glass. The back focal length of the objective is 103.8 mm and NA = 0.24. Residual comma aberrations are presented at different imaging fields of view. Spot size increases from 0.006 mm in the on-axis view to 0.018 mm for full field of the triplet. Calculated radial fractional energy distributions versus spot radius at different angles of the incident rays are presented. The charts show good aberration correction of the objective in case of on-axis view in the focal plane.

When service temperature varies in broad limits additional thermo-optic aberrations appear due to $\mathrm{d}n/\mathrm{d}T$ changes and variation of radius of curvature of the refractive surfaces connected with the high values of thermal expansion coefficients of OPs. Consequently thermally-induced optical figure errors of polymer elements arise. Detailed analysis of thermo-optic aberrations of plastic devices could be accomplished in accordance with [8].

4 Conclusions

Possible applications of OPs are defined mainly by their optical properties in terms of refractive indices, transmission, dispersion and thermo-optic coefficients. On base of measured refractometric data dispersive parameters of OPs are calculated. Abbe numbers, principal, partial and relative partial dispersions in VIS and NIR regions are estimated to support the optical design of all-plastic or hybrid elements. Our analysis confirms that optical properties of OPs are sufficiently good for precise imaging applications. Comparison to glasses is carried out to confirm their usage and compatibility in hybrid optics. Incorporation of polymer and glass types may result in thermally stable and well-corrected optical systems. OPs are higher dispersive materials than glasses in the VIS light but may show lower dispersion in the NIR spectrum and therefore seem to be suitable materials for night vision applications.

Calculated refractometric, dispersive and thermo-optic characteristics of polymer materials could be useful in the design of optical elements and devices.

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