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Optical properties of plastic materials for medical vision applications

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Abstract. Several types of optical polymer materials suitable for ophthalmic or medical vision applications have been studied. We have measured refractive indices of studied plastics at various wavelengths in the visible and near-infrared spectral regions. Important optical characteristics as Abbe numbers, dispersion coefficients and curves, principal and relative partial dispersion have been evaluated. Calculated refractometric data at many laser emission wavelengths used for medical surgery, therapy and diagnostics is included. As an example of a medical vision application of plastics, optical design of a micro-triplet for use in disposable endoscopes is presented.

1. Introduction

The variety of medical applications of optical plastic materials expands in consumer optics as well as in high precision vision devices. Over 50 percent of all eyeglass lenses sold nowadays are made of organic polymers. Except in ophthalmology, many surgical and diagnostic instruments as laparoscopes, arthroscopes, cystoscopes, endoscopes, etc. apply plastic materials [1]. The use of polymer optics is found in a wide range of not only clinical vision applications such as digital cameras, fiber photonic elements and systems, microscopes, surgical head-mounted video displays, LCD projectors, videoconferencing devices and mobile imaging. The rapid development of microelectronics and semiconductor industries places high demands on the performance of the applied miniature optical elements. Improvements in polymer and integrated hybrid glass-polymer components and systems offer efficient and compact solutions to meet these demands [2].

Optical polymers (OPs) have several key advantages over glasses as reduced weight and cost, high impact and shatter resistance and ability to integrate proper mechanical and optical features [1]. The injection-moulding process is very effective to reproduce not only spherical but sophisticated optical shapes such as aspheres, and other complex geometric surfaces or elements with noncircular apertures. Obviously, unique priority of polymers in medical applications is safety. The major drawbacks of plastic materials are that they have less scratch resistance and are more sensitive to environment changes such as temperature and humidity. Plastics lenses can be supplied with hard, anti-abrasion coatings with anti-static and hydrophobic properties, helping to maintain the transparency of the surfaces and making them easier to clean [3]. Broad thermal range functionality and better correction of aberrations of medical vision components and devices can be achieved by usage of hybrid glass-polymer optics. Incorporation of plastics and glass may result in low-cost, high-performance and high-

volume optics.

Application of OPs in the design of optical elements and devices requires the knowledge of their refractometric and dispersive characteristics. We have studied optical properties of more than twenty types of transparent plastics, including principal and some new development polymers [4, 5]. A few of them, however, are suitable for ophthalmic or medical vision applications. Most popular for this purpose are materials as acrylic based polymers, polycarbonates, allyl diglycol carbonates, cyclo olefin polymers and copolymers, polystyrenes, alicyclic methacrylate copolymers. On the base of measured extensive refractometric data of such plastic samples at various wavelengths in the visible (VIS) and near-infrared (NIR) regions we have evaluated optical characteristics of studied materials as Abbe numbers, dispersive coefficients and curves, principal and relative partial dispersions. Influence of temperature on refraction of polymer media is experimentally determined and their thermo-optic coefficients are presented. Comparison to some glass types is carried out to confirm the optical quality of OPs and optimize material selection in accordance to consumer's preferences or vision system requirements.

2. Experimental

Several methods were applied to obtain refractometric data of OPs. In the VIS range of spectrum we have used the Carl Zeiss Jena Pulfrich-Refractometer PR2 with its V-type SF3 glass prism. Measurements are based on the deviation angle method. Samples were produced as injection moulded plates or cubes with two fairly well polished, mutually perpendicular surfaces to obtain good refractometric data [4,5]. Proper immersion emulsions with a suitable refractive index were used to ensure the optical contact between the plastic samples and the prism. Measuring temperature of 20°C was maintained and temperature regulation was possible with stability of 0.2°C. Refractive indices were measured at the emission wavelengths of the spectral lamps of the PR2 instrument in the VIS region: for the mercury source at the green e-line 546.07 nm and blue g-line 435.83 nm, for the helium source at the yellow d-line 587.56 nm, and for the hydrogen source at the blue F-line 486.13 nm, and red C-line 656.27 nm. Measurement accuracy of the Pulfrich-Refractometer is 2×10^{-5} [6].

The V-type prism with its thermostatic housing is suitable to obtain refractometric data at varying temperature. Some of the polymers were measured in the range between 10 and 50 °C using a MLW thermostat U4 with water bath, made in Germany. Thus influence of temperature on refraction of OPs was investigated.

Additional goniometric set-up with the same prism, a white lighting module (a 250 W halogen lamp and a condenser system) with interference filters (IFs) and a photo detector device was applied for measuring in the entire VIS and NIR regions. The transmission maxima of the applied IFs are as follows: 548, 589, 597, 659, 703 nm for the VIS region, and 752, 804, 833, 879 and 1052 nm for the NIR spectrum. A G5-LOMO goniometer with an accuracy of one arc second was used to measure the deviation angle. Comparison between the obtained results by the PR2 refractometer and the goniometric set-up in VIS light was possible. The metrological tests in [4] pointed out that our measurements of the OPs' indices guarantee accuracy better than ± 0.001 . A number of polymer specimens have been measured with this goniometric set-up and a He-Ne laser at 632.8 nm as a lighting module [7].

Transmission of studied OPs was measured in the spectral range from 400 to 2500 nm using a UV-VIS-NIR spectrophotometer Varian Carry 5E. For this purpose thin polymer films with varying thickness have been produced by dissolving some of the polymers in proper organic solvents [8].

3. Optical characteristics

3.1. Refraction

Among studied polymers with medical purpose applications are polymethyl methacrylate (PMMA), polystyrene (PS), polycarbonate (PC), cyclo olefin plastic Zeonex E48R, alicyclic methacrylate copolymer Optorez 1330 and Bayer which is a polycarbonate material. Measured refractive indices at

eight wavelengths are presented in table 1. Columns 1, 2, 3 and 5 refer to the indices obtained by means of the PR2 instrument and the rest of the columns – the results received on the goniometric set-up. Column 4 presents laser measurements at emission wavelength 632.8 nm. Additional refractometric data at the d-line is included in table 2 to make more convenient the comparison to optical glass types with similar refraction.

Table 1. Measured refractive indices of OPs.

OPs	Wavelength [nm]							
	435.8	486.1	546.1	632.8	656.3	703	879	1052
	1	2	3	4	5	6	7	8
PMMA	1.5025	1.4973	1.4934	1.4890	1.4890	1.4863	1.4835	1.4813
PS	1.6171	1.6056	1.5963	1.5872	1.5862	1.5820	1.5756	1.5718
PC	1.6117	1.5994	1.5896	1.5802	1.5793	1.5749	1.5683	1.5645
Optorez 1330	1.5219	1.5163	1.5119	1.5075	1.5065	1.5054	1.5021	1.4984
Zeonex E48R	1.5431	1.5376	1.5333	1.5284	1.5282	1.5256	1.5224	1.5204
Bayer	1.6121	1.5998	1.5905	1.5814	1.5803	1.5765	1.5698	1.5660

Presented data reveals a monotonous decrease of refractive indices with increasing wavelength of all studied polymers which confirms their normal dispersion behaviour in the measuring spectral region from 435 to 1052 nm. On the base of the experimentally obtained results we analyse the dispersive properties of OPs and comparison to optical glass is possible.

The range of refractive index values of plastics is much more restricted compared to glass. Glass catalogues propose materials with refraction usually between 1.49 up to 1.90 at the d-line but special products with n_d of about 1.43 and 2.01 are also available [9, 10]. Measured data of n_d of all of the examined OPs varies in a limited interval from 1.47 for the Cellulose material [5] up to 1.59 for the PS polymer (table 2). Recently, developing the technological processes some companies report for special plastics with n_d as high as 1.74 [11]. Nevertheless, designers have at their disposal not as many optical-grade polymers as compared to glass.

In table 2 we present optical characteristics of measured OPs (columns 1-5). Column 6 refers to the one of the most frequently used in ophthalmology CR39 plastic which is an allyl diglycol carbonate material produced by PPG Industries [12]. The included types of optical glass in columns 7 and 8 are also for ophthalmic use and column 9 presents cited data of the popular SCHOTT glass N-BK10 [9]. HC-Weiss 0290 and Unicrown materials are trademarks of spectacle glass types of Barberini [13] and Corning [14] companies, respectively.

Table 2. Optical characteristics of OPs and selected glass types.

Characteristics	PMMA	PS	PC	Optorez 1330	Zeonex E48R	CR39	HC-Weiss 0290	Uni-crown	N-BK10
	1	2	3	4	5	6	7	8	9
n_d	1.4914	1.5917	1.5849	1.5094	1.5309	1.4985	1.6008	1.5230	1.4978
$n_F - n_C$	0.0083	0.0194	0.0201	0.0098	0.0094	0.0084	0.0136	0.0089	0.0074
v_d	59.2	30.5	29.1	52.0	56.5	59.3	44.2	58.8	66.95
$P_{g,F}$	0.626	0.593	0.612	0.571	0.585	–	0.573	0.590	0.530
$P_{d,C}$	0.289	0.283	0.279	0.296	0.287	0.345	0.301	0.303	0.309
$\Delta n_c / \Delta T \times 10^{-6} / K$	-130	-131	-100	-120	-126	–	–	–	3.4
UV cut-off [nm]	360 ^[15]	390	380 ^[16]	–	340 ^[17]	355 ^[12]	330 ^[13]	320 ^[14]	270 ^[9]

The significant influence of temperature on refraction of polymers is demonstrated by the presented

in table 2 values of the calculated gradient $\Delta n_e / \Delta T$ for the range 20÷40 °C. Measured n_g , n_F , n_e , n_d , n_C values of studied polymers decrease with increasing temperature [18]. Thermal properties of plastics are rather different compared to glass and this fact should be carefully regarded in medical vision applications. The thermo-optic coefficients of OPs are negative and contrast to the positive coefficients of almost all optical glass types. Their absolute values are with about two orders of magnitude larger than those for glass [9-11]. It seems that integration of plastic and glass materials in a hybrid component may result in its thermal stability suitable for high performance medical imaging systems. A polymer layer can be laid on the glass body for stable thermal behaviour of the hybrid.

3.2. Dispersion

Important optical parameters in the design of vision systems are Abbe numbers v_d or v_e , principal dispersion $n_F - n_C$ and relative partial dispersions $P_{x,y}$ at selected wavelengths x and y . In table 2 these characteristics are presented for studied OPs while the respective values for the CR39 ophthalmic material and considered glass types are evaluated on base of catalogue data. Included relative partial dispersions are calculated by the following relations:

$$P_{g,F} = \frac{n_g - n_F}{n_F - n_C} \quad \text{and} \quad P_{d,C} = \frac{n_d - n_C}{n_F - n_C}. \quad (1)$$

These characteristics are important for chromatic correction. In the design of multiple component optical systems partial dispersions should be closely matched while Abbe numbers differ substantially. As for example, in the VIS region the PMMA could be combined with the PS or PC material in a plastic doublet. The Zeonex material and PS plastic also form a suitable achromatic pair.

In figure 1(a) the optical scheme of all-plastic endoscopic micro-objective is proposed as an example of a medical vision application. The purpose of such objectives is to form and process qualitative colour images of investigated human tissues and organs. High performance endoscopes are expensive and their multiple usages require time-consuming and exhaustive cleaning procedures every time they are used. This problem might be solved by low cost but reliable disposable endoscopes. The presented wide-angle triplet is made of PMMA and PS plastics for better colour image correction. In figure 1(b) residual coma aberrations, calculated by means of OSLO optical program, are presented at different imaging field of view. Spot size increases from 0.009 mm in on-axis view to 0.015 mm for the full field of the triplet. Calculated diffractive point spread functions (DPSFs) and fractional energy versus spot radius are illustrated in figure 1(c) again at different angles of the incident rays. The charts show good aberration correction of the micro-objective in case of on-axis view in the focal plane.

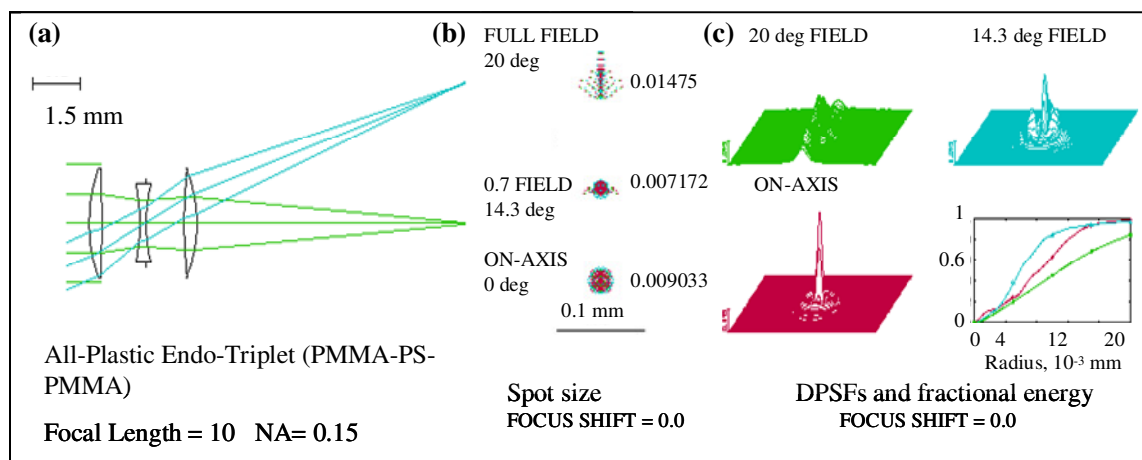


Figure 1. Optical scheme and aberrations of endoscopic triplet.

Our results show that OPs transmit well in the VIS and NIR regions and have transmittance better than 90% in the considered spectral range from 430 to 1100 nm [8]. Requirements of ISO standards for ophthalmic materials include information on the ultraviolet (UV) cut-off point. Therefore, in table 2 we present this data, since the UV radiation contributes to the development of various ocular disorders. As it can be seen, high refractive lens materials generally absorb more UV light. Ordinary glasses absorb UV rays with wavelengths under 300 nm and IR light over 3500 nm but some ophthalmic types as HC-Weiss 0290 and Unicrown have a little bit higher UV cut-off. Plastic lenses do not protect the eye from UV rays unless properly tinted. Different UV inhibitors should be added to polymers or tinting by organic dyes of lens surfaces is carried out to decrease the UV absorption.

Obtained transmission spectra as well as presented refractive data of studied OPs reveal their normal dispersion properties. We have applied the Cauchy-Schott's formula involving six dispersion coefficients which assures calculation accuracy better than ± 0.0001 in the VIS and NIR regions from 435.8 to 1052 nm [5]:

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

where A_1, \dots, A_6 are the Cauchy's coefficients. A program OptiColor was realized on the base of equation (2) that allows us calculation of dispersion coefficients, charts, Abbe numbers and random values of refractive indices. The input data consists of six measured indices at selected wavelengths and a linear system of equations is solved to compute the Cauchy's coefficients. Obtained dispersion charts of some of the studied polymers are illustrated in figure 2(a) in the whole considered spectral region. Higher refractive materials have steeper curves and therefore exhibit greater dispersion.

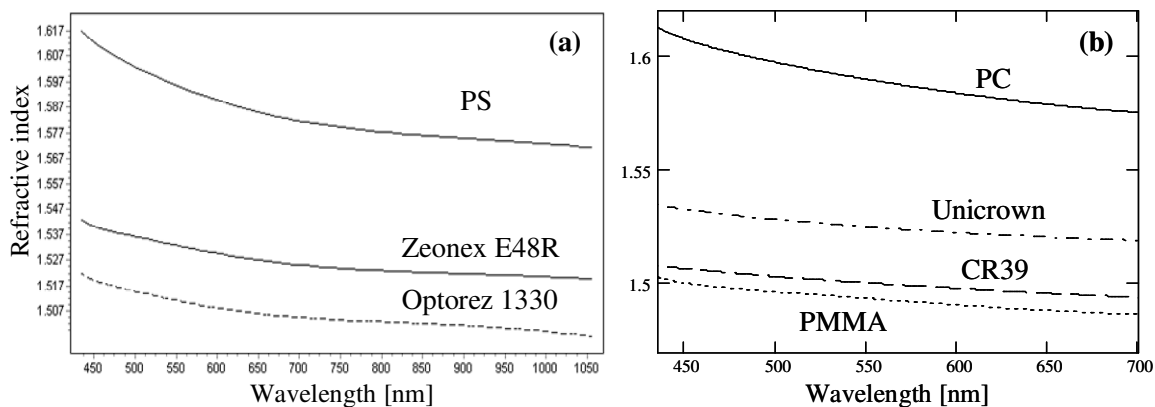


Figure 2. Dispersion charts of (a) principal OPs; (b) ophthalmic OPs and glass.

In figure 2(b) graphs of some ophthalmic OPs and the Corning Unicrown type glass are shown. Because of lack of sufficient refractometric data for the CR39 plastic, which is most frequently used for vision corrections, dispersion coefficients and charts have been calculated in the VIS light using only three terms of the series in equation 2. The curves of PMMA and CR39 as well as their Abbe numbers (table 2) confirm their low dispersion. However, the CR39 material is preferred in ophthalmic applications because it is harder and more resistant to scratches than other plastic lens materials. The Unicrown spectacle glass is also with similar dispersion. Our investigations on more than twenty optical polymers prove that OPs are higher dispersive materials in VIS light but may have similar or lower dispersion in NIR spectrum [19]. This fact makes them preferable materials in night vision photonic instruments.

Medical lasers appear in surgical and many non-surgical treatments in cosmetics, dentistry, therapy and vision diagnostic or biomedical analysers. In all cases light is transmitted by means of all-plastic

or hybrid glass-plastic optics. In table 3 calculated refractive indices at emission wavelengths of some commercial medical lasers, including diode lasers, are presented. Data may be useful for designers of laser devices.

Table 3. Calculated refractive indices at laser emission wavelengths.

OPs	Laser emission wavelength [nm]								
	430	457.1	488	515	532	670	785	867	980
PMMA	1.504	1.499	1.497	1.486	1.495	1.487	1.484	1.483	1.482
PS	1.619	1.611	1.605	1.601	1.599	1.584	1.578	1.576	1.574
PC	1.614	1.605	1.599	1.595	1.592	1.577	1.571	1.569	1.566
Optorez 1330	1.523	1.519	1.516	1.514	1.513	1.506	1.504	1.502	1.500
Zeonex E48R	1.544	1.540	1.537	1.364	1.534	1.527	1.524	1.523	1.522
Bayer	1.614	1.605	1.599	1.954	1.592	1.577	1.571	1.569	1.566

4. Conclusions

Our investigations on optical properties of OPs reveal their appropriate characteristics and compatibility with glass for application in all-plastic or hybrid glass-plastic optics for medical vision devices and systems. Refractive, as well as dispersive parameters of polymers conform to their implementation in well corrected and high performance medical imaging components. Because of safety and twice lower weight OPs are preferable materials in consumer optics. Ophthalmic plastics allow for production of thinner, lightest lenses possible at reduced price. Some of their drawbacks as low scratch resistance and UV absorption can be surmounted by special coatings or tinting. Attention should be drawn to the influence of temperature on refraction and dispersion of polymers.

Plastic optics offers additional design freedoms that are not achievable or economical with glass optics.

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