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Advanced Applications of Optical Polymers

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Abstract. Optical and some thermal characteristics of a number of polymers have been studied to confirm their application in the design of optical systems. Transmission spectra and refractive indices have been measured in the visible and near-infrared region. Influence of temperature on refraction is considered. The design of two polymer micro-lenses is accomplished.

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1 Introduction

Advanced applications of optical polymers (OPs) include optoelectronic and communication systems, military and space fabrication, biomedical polymer production, composites produced with polymer nano-fibers and nanoparticles, multilayered polymer-semiconductor sandwiches, smart materials as hybrid polymer-metal and polymer-glass assembled constructions, ultra-high density optical memories, neural networks, adaptive artificial vision systems, molecular machines, nano-robots, etc. [1-4]. The polymer developed micro- and nano-optoelectronic components is a leading segment for producing smart optics having superior information speeds and data transfer rates which can be manufactured with nanoscale integration on a chip [5].

Selection of polymers in optical applications is accomplished on base of their spectral transmission, refractive index (RI) and dispersion. Birefringence, striation, haze, stability to environmental conditions, light or thermal discoloration (yellowing) of the material, ultraviolet (UV) or ionizing exposure degradation, etc. influence the optical quality of fabricated polymer elements. Inhibitors, anti-reflective and anti-abrasive coatings with anti-static and hydrophobic behaviour are applied to improve polymer properties and to retard UV crosslinking. Birefringence better than 8×10^{-3} for polystyrene and 6×10^{-5} for acrylic polymers should be controlled during injection moulding of optical elements [6]. Mechanical and thermal properties of OPs are important in lens design, too. Though polymers are preferred materials in contemporary optics because of their low weight and cost as well as high impact resistance, their thermal sensitivity is a great disadvantage in comparison to glasses. Thermal expansion of OPs and RI variation with temperature should be regarded to achieve athermalization of the end polymer product applying hybrid glass-plastic elements and proper material housing [7].

We have studied various types of American, German and Japanese polymers, including principal thermoplastics as PMMA, PS and PC, copolymers SAN and NAS, many trademarks as CTE-Richardson, Zeonex E48R, Optorez 1330, NAS 21 Novacor, Bayer, and some development materials, produced by the USA Eastman Chemical Company. Bulk polymer samples as well as thin films have been considered. Different measuring techniques have been applied to obtain RIs in the visible (VIS) and near-infrared (NIR) regions. Our results show differences in refraction of bulk polymers and polymer layers for one and the same material [8]. In this study we present refractive and dispersive characteristics of bulk OPs which are used in the design of optical components. Thermal sensitivity of polymers is analysed on base of their thermo-optic and thermal expansion coefficients as well as thermal "glass" constant.

Two examples of optical design of polymer micro-lenses are presented. A DVD blu-ray objective and an all-mirror apochromat intended for laser diode fiber coupling at 1350 and 1500 nm in optical communication systems are synthesized. Geometric and wavefront aberrations are computed to evaluate image quality of the proposed optical systems.

2 Characteristics of Polymers for Lens Design

Optical behaviour of lens materials is defined mainly by their transmittance, refraction and dispersion in the respective spectral area. Measured transmission spectra of thin polymer films of studied materials confirm transmittance better than 85% in the VIS and NIR regions up to 1730 nm [7]. Obtained spectra have weak absorption bands between 1660 and 1700 nm, due to the first overtone of the –CH group and a considerable transmission decrease is observed at wavelengths greater than 2200 nm where absorption of other C–H groups occurs. Optical losses of polymers are low in the three telecommunication windows around 850, 1310 and 1550 nm and therefore OPs are widely used in fiber optics. Typically, polymers are totally opaque in the UV and with very low transmittance beyond 2100 nm.

RI value n is one of the most important parameter for selection of a plastic in optical design. We have measured refraction of OPs at 22 wavelengths λ in the interval $406 \div 1320$ nm. Results for bulk polymer samples are obtained at 16 wavelengths in the diapason $435 \div 1052$ nm by means of Pulfrich refractometer in VIS light with an instrumental error of 2×10^{-5} and a laboratory assembled goniometric set-up for VIS and NIR spectra with an uncertainty of $\pm(3.6 \div 3.9) \times 10^{-4}$ [8]. RIs at common wavelengths obtained by both techniques coincide in the limits of 9×10^{-4}. Measured RIs at 20°C are included in Table 1. The results at GaN diode laser emission $\lambda = 405$ nm are computed by means of our software program OptiColor based on the Cauchy–Schott approximation for normal dispersion. Calculation accuracy of random RIs is $\pm 1 \times 10^{-5}$ in the interval $435.8 \div 1052$ nm, $\pm 1 \times 10^{-4}$ for wavelengths at the beginning of VIS area, and about $\pm 5 \times 10^{-4}$ at λ close to 1500 nm [8]. RIs of most OPs vary in a rather limited range of values $1.49 \div 1.59$ at the d-line (587.6 nm) which restricts choice of materials in optical design. Higher refractive plastics are being developed by Hoya Company and Mitsui Chemicals.

Table 1: Refractive, dispersive and thermal characteristics of some OPs

	PMMA	Zeonex E48R	Optorez 1330	SAN	PS	Bayer	PC
n_{405}	1.5156	1.5544	1.5262	1.6072	1.6328	1.6273	1.6297
n_g	1.5025	1.5431	1.5219	1.5882	1.6171	1.6121	1.6117
n_d	1.4914	1.5309	1.5094	1.5667	1.5917	1.5857	1.5849
n_{879}	1.4834	1.5225	1.5017	1.5527	1.5755	1.5698	1.5683
n_{1052}	1.4813	1.5204	1.4984	1.5496	1.5718	1.5661	1.5645
$n_F - n_C$	0.0083	0.0094	0.0098	0.0160	0.0194	0.0195	0.0201
$n_g - n_F$	0.0052	0.0055	0.0056	0.0099	0.0115	0.0123	0.0123
$n_s - n_t$	0.0021	0.0019	0.0030	0.0028	0.0036	0.0036	0.0036
ν_d	59.2	56.5	52.0	35.4	30.5	30.0	29.1
ν_{879}	97.6	100.5	71.7	66.6	55.9	54.8	54.6
$P_{g,F}$	0.626	0.585	0.571	0.619	0.593	0.631	0.612
$P_{s,t}$	0.217	0.191	0.306	0.175	0.186	0.164	0.179
$\Delta n_g/\Delta T,\ \times 10^{-4}\ \mathrm{K}^{-1}$	-1.32	-1.30	-1.22	-1.20	-1.37	-1.22	-1.10
$\Delta n_C/\Delta T,\ \times 10^{-4}\ \mathrm{K}^{-1}$	-1.28	-1.20	-1.16	-1.05	-1.26	-1.18	-1.00
$\alpha,\ \times 10^{-4}\ \mathrm{K}^{-1}$	0.75	0.66	0.67	0.53	0.60	0.56	0.47
$\gamma_g,\ \times 10^{-4}\mathrm{K}^{-1}$	-3.38	-3.06	-3.00	-2.57	-2.82	-2.55	-2.26
$\gamma_C,\ \times 10^{-4}\mathrm{K}^{-1}$	-3.37	-2.94	-2.96	-2.40	-2.75	-2.59	-2.19

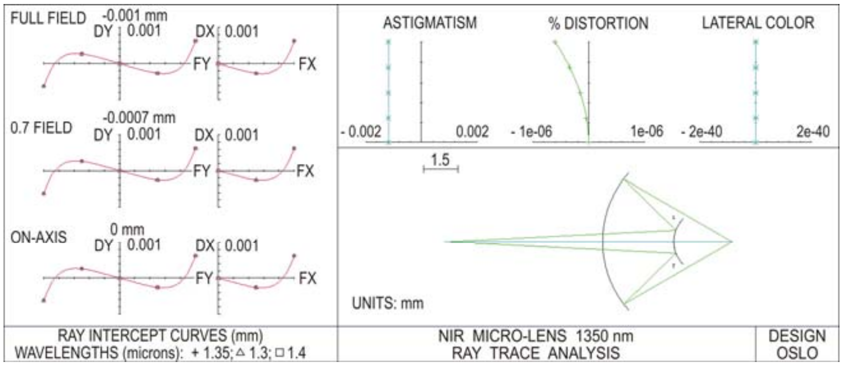
Dispersion properties of materials are essential for the image quality in optical design. They are usually evaluated by Abbe numbers, principal, partial and relative partial dispersions. The dispersive characteristics in Table 1 are used in the presented optical design examples. OPs are set in the order of decreasing value of ν_d and increasing principal dispersion $n_F - n_C$. Values of partial dispersions $n_g - n_F$ and $n_s - n_t$ show that all OPs are more dispersive in the blue part of the VIS region while dispersion in NIR spectrum is negligible. Wavelengths at selected Fraunhofer spectral lines are as follows: 435.8 (g-), 486.1 (F-), 656.3 (C-), 852.1 (s-), and 1013.9 nm (t-line). Usually higher refractive materials are more dispersive but it is not always true. The PC plastic is more dispersive than PS and the same relation is established for the Optorez and Zeonex polymers in VIS light. In the NIR spectrum, additional Abbe number is introduced as: $\nu_{879} = (n_{879} - 1)/(n_{703} - n_{1052})$, where measured RIs by the goniometric set-up are used. The least dispersive material is the Zeonex E48R polymer. For better colour correction of achromatic pairs, relative partial dispersions of selected OPs should be similar while Abbe numbers differ substantially for the specified spectral area.

Service temperatures of polymer optics are usually between -$40 \div 60°$C. Among all OPs, the PC material is with broadest operating band -$137\div$ +$130°$C [8]. Temperature variations induce thermo-optical aberrations due to RI alteration and dimensional changes of polymer objectives. The temperature gradient $\Delta n/\Delta T$ is known in literature as thermo-optic coefficient (TOC). We have measured RIs of studied OPs in the range between 10 and 50°C at the spectral lines of the Pulfrich refractometer. Results for the g- and C-line are included in Table 1. In comparison to glasses, TOC absolute values of OPs are with about two orders of magnitude larger than those for optical glass types but are always negative. Variation of TOCs with λ is noticed and slight alteration of dispersive parameters is established. The linear thermal expansion coefficient α is estimated on base of Lorentz–Lorenz equation and results at the d-line are presented in the table. OPs typically show α values 10 times higher than those of metals and 20 times higher than those of glasses.

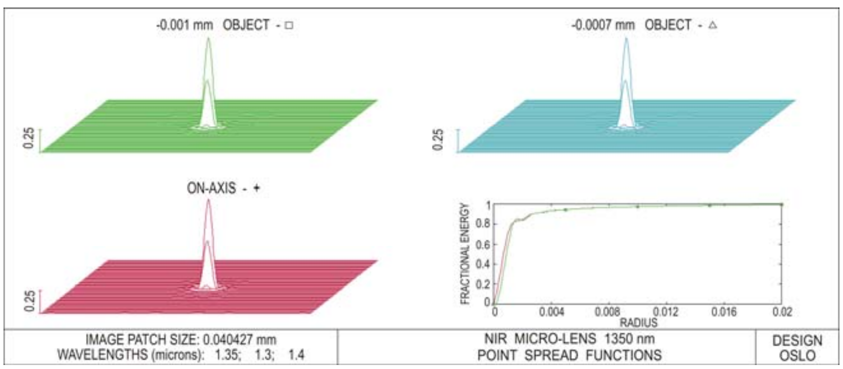
In lens design, the parameter thermal "glass" constant (TGC) $\gamma_{\lambda,T}$ is used to characterize the change in optical path length with temperature: $\gamma_{\lambda,T} = [dn_\lambda/dT/(n_\lambda - 1)] - \alpha$. In Table 1, values of TGCs of studied OPs are given at g- and C-line and as it is seen the results are negative. Thermal defocus Δf of optical elements is influenced by the TGC of the lens material and the thermal expansion coefficient of the housing α_h [9]. For a single thin lens with a focal length $f : \Delta f = -f(\gamma_{\lambda,T} + \alpha_h)\Delta T$. In case of polymer optics, elongation of focal length is observed with increasing temperature. Partial athermalization is possible by proper selection of lens and housing materials. Tolerable temperature change of the designed optical system is in addition proportional to the applied wavelength and numerical aperture.

3 Applications of Polymer Materials in Micro-Focusing Lenses

The design of a micro-lens with a focal length $f' = 1.038$ mm and numerical aperture NA = 0.5 is illustrated in Figure 1a. The objective is



a)



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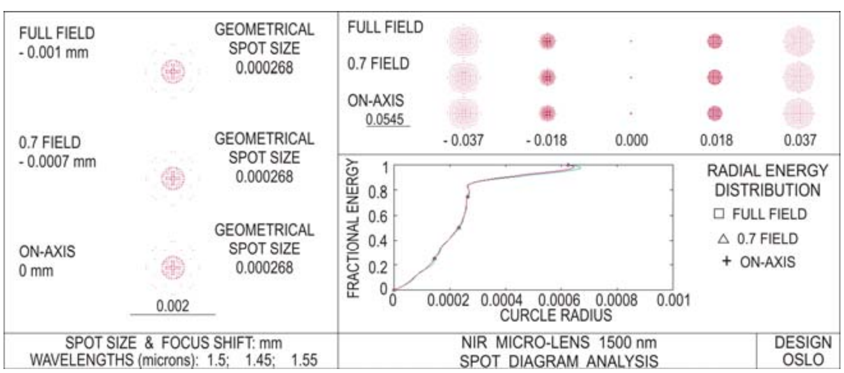

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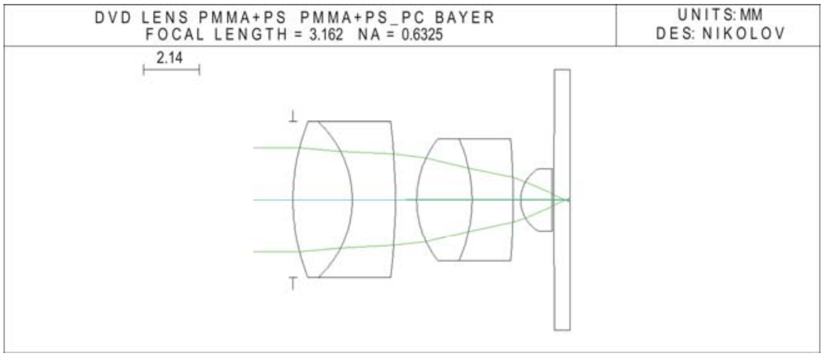
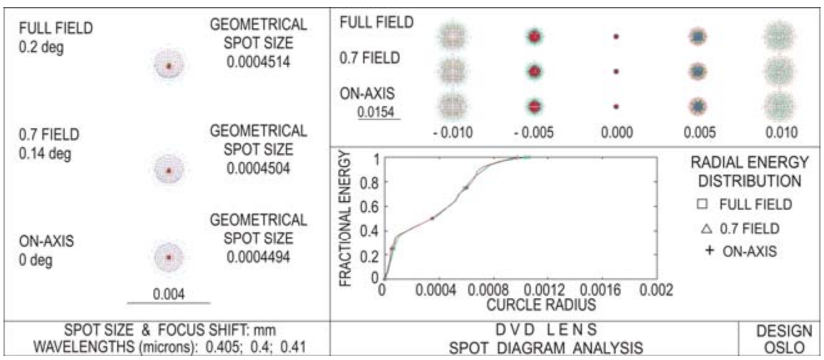
Figure 1: All-mirror plastic NIR micro-lens: a) optical scheme and geometrical aberrations; b) point spread functions and energy distribution at 1350 nm; c) spot diagram analysis at 1500 nm.



a)



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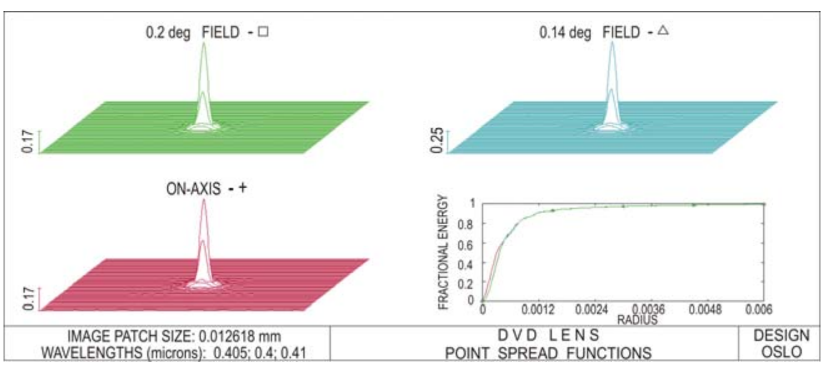

c)

Figure 2: DVD blu-ray micro-objective: a) optical scheme; b) spot diagram analysis; and c) point spread functions.

intended for laser fiber coupling in optical communication lines in the NIR spectral region at wavelengths of 1350 and 1500 nm. NA of the proposed system may vary in the diapason from 0.1 to 0.5 in respect to the aperture of the used optical fiber. This apochromat is built by two PC mirrored spherical shells which are sputtered with aluminum reflective layers and silicon oxide anti-abrasive films.

Geometrical and wavefront aberrations have been calculated by means of OSLO software program. Results at 1350 nm are presented in Figure 1a,b and spot diagram analysis at 1500 nm is illustrated in Figure 1c. The proposed system is characterized with high transmittance in the entire spectral region $250 \div 1500$ nm and lack of any chromatic aberrations. Thermal aberrations, in this case, are not influenced by the RI alteration of the PC material with T and the change of the focal length is determined only by the radius of surface curvature r of the mirrors, linear thermal expansion coefficient of the polymer and temperature interval: $\Delta f' = 0.5 r \alpha \Delta T$.

In data recording devices, aberration-free objectives with high numerical apertures are applied. The optical requirements are as follow: focal length from 3 mm to 10 mm, numerical aperture from 0.4 to 0.8, focused spot diameter under 0.4 μm, image field 0.05–0.25 mm and mass under 5 g [10]. The optical scheme of the designed blu-ray DVD monochromat with $f' = 3.162$ mm and NA = 0.6325 is presented in Figure 2a. This micro-objective consists of two PMMA-PS achromats and a solid immersion PC lens with 0.6 mm Bayer disk. Combination of PMMA-PC in achromat is with lower chromatic balancing (Table 1). Computed spot diagrams are illustrated in Figure 2b. Spot sizes vary slightly at the three fields of view and are about 0.45 μm which is under the required 0.58 μm blu-ray disc resolution. The geometrical spot function is about 0.6 μm at 0.8 of the fractional energy. Calculated point spread functions are presented in Figure 2c with radii under 0.8 μm at level of 0.8 of the fractional energy.

4 Conclusions

Selection of OPs in lens design is accomplished on base of their optical, material, thermal and environmental properties. Plastics are organic glasses with good transmission in VIS and NIR regions. On base of measured RIs, dispersive and thermo-optical parameters are determined (Table 1). Characteristics of OPs are sufficiently good for precise imaging applications. Dispersion in VIS light is commonly higher than glasses and may be extremely low in the NIR region (PMMA, Zeonex E48R). Abbe numbers, principal, partial and relative partial dispersions are estimated to be used in the design of optical polymer systems. Among studied OPs, Bayer and PC may form achromatic pair with PMMA at shorter wavelengths in VIS light and PS with PMMA is suitable pair in the NIR region (Figure 2). PC mirrored surfaces are introduced to reduce the end micro-lens weight and dimensions (Figure 1). The system is characterized with an increased relative aperture at high image quality. Thermal aberrations may be reduced by proper choice of lens and housing materials. Polymer micro-lenses might be successfully used for fiber couplers and connectors in optical communication networks, video and still cameras, medical vision devices, light-emitting diodes, light guides, optical storage media, and so on.

The polymer developed optoelectronic components will be the leading segment for producing smart optics.

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