OPTICAL POLYMERS IN REMOTE IMAGING DEVICES

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Abstract: *We have investigated optical properties and some material characteristics of various types of polymers including principal, many trade-marks and development plastics. Refraction of bulk samples as well as thin layers has been measured in the spectral region between 400 and 1300 nm and transmission is investigated in the diapason 400-2500 nm. Selection of polymers in remote imaging systems is accomplished on base of their refractive, dispersive and thermal characteristics. Refractive indices, Abbe numbers, principal, partial and relative partial dispersions are presented. Influence of temperature on optical properties is considered. Optical design of a Newton type polymer mirror-lens objective is presented. The system is intended for remote imaging of contaminated ground areas. Geometrical aberrations are computed to verify image quality.*

ПРИЛОЖЕНИЕ НА ОПТИЧНИТЕ ПОЛИМЕРИ В УРЕДИ ЗА ДИСТАНЦИОННО НАБЛЮДЕНИЕ

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Ключови думи: *Оптични полимери, дистанционно наблюдение, оптичен дизйн на полимерни обективи*

Резюме: *Изследвани са оптичните свойства и някои материални характеристики на голям брой оптични полимери, включващи както основни, така и развойни материали и някои търговски марки. Измерени са показателите на пречупване на тънкослойни и обемни полимерни образци в спектралния диапазон от 400 до 1300 nm и трансмисионни спектри от 400 до 2500 nm. Изборът на подходящи полимери за обективи в системи за дистанционно наблюдение се базира на техните рефракционни, дисперсионни и топлинни характеристики. Разгледани са показателите им на пречупване, числата на Аббе, средни, частни и относителни частни дисперсии. Изследвано е влиянието на температурата върху оптичните свойства на полимерите. Представен е дизайнът на огледално-лещов полимерен обектив, тип Нютон, за дистанционно наблюдение на земни повърхности. Качеството на образа е оценено чрез изчислените аберации.*

Introduction

Polymers are preferable materials in optical instruments, data recording devices, optical communications, displays, light-emitting diodes, etc., because of their low cost, reduced weight, flexibility and excellent transmittance in the visible and near-infrared spectra [1]. Injection moulding technology offers high-volume production of complex optical surfaces and multifunctional components. Polymers integrate proper mechanical and optical features. They exhibit high impact and shatter resistance and are preferred materials in aircraft equipment where safety and reliability is an important factor. Thermal instability of polymers is possible to be reduced in hybrid glass-plastic optical systems while proper choice of housing materials minimizes thermal aberrations [2]. Polymer films over glass components are used in high-performance imaging optics or in production of optical sensors, fibers and waveguides.

Polymers are successfully applied in aerospace optical technologies. They are widely used in LED displays for interactive visualization and satellite telecommunications, starting from smart phones to complex systems for geophysical and meteorological investigations, lidar measurements, multispectral cameras for remote imaging of land or ocean surfaces and atmosphere. Advanced materials are used in high-technological space applications. New hybrid and nanocomposite polymer structures are used in laser systems, optical memories, holographic media, photonic and plasmonic modules, optoelectronic components, hybrid objectives and so on. Smart materials as hybrid polymer-metal and polymer-glass assembled constructions, metal skeletons and grids fabricated in polymer matrixes, metal surfaces with implanted polymer molecular layers, polymer components integrated with metal atomic films is a leading segment in materials sciences, mechanical, aerospace, military, etc. engineering.

Remote sensing and imaging instruments with polymer optics are widely used for measuring from satellite-, aircraft-, and ground-based laboratories [2]. Different types of video spectrometers from multi- through hyper- to ultra-spectral are applied to gather detailed information of the investigated surface. Data processing of spectral luminance is used for numerous ranges of purposes such as identification of minerals in rocks and soil, measured organic content, pollution of oceans and groundwater, etc. Helmet mounted displays facilitate visual information in front of eyes of pilots and astronauts in real time. They are assembled with different optical polymer systems as magnifiers, goggles, targeting information, measuring screens, etc. Since 2008 colour LCD modules for helmets are produced with polymer viewfinders and panoramic night-vision goggles. In 2014 a new visualizing system F-35 Lightning II is made which provides pilots with unprecedented situational awareness as air speed, altitude, targeting information and warnings as well as real-time imagery from six infrared cameras mounted around the aircraft to the helmet.

Different optical polymers (OPs), including principal as polymethyl methacrylate (PMMA), polystyrene (PS), polycarbonate (PC), methyl methacrylate styrene copolymer (NAS), styrene acrylonitrile (SAN), some trade-marks of OPs as NAS-21 Novacor, CTE-Richardson, Zeonex E48R, Bayer, and development materials of Eastman Chemical Company (ECC) have been investigated. Refractometric measurements of bulk polymer samples and thin films have been accomplished in the entire visible (VIS) and near-infrared (NIR) spectral regions up to 1320 nm. Transmission spectra from 400 to 2500 nm have been measured, too. Dispersion curves and characteristics have been determined. Different optical properties of bulk polymers and thin films are pointed out. Influence of temperature on refraction is investigated by means of their thermo-optic coefficients, linear and volume thermal expansion and thermal “glass” constants.

Objectives with excellent optical characteristics and aberration corrections in the full field of view are required in remote imaging devices. The optical design of a Newton-type mirror-lens objective is presented to illustrate application of polymers in high quality optics.

Properties of polymer materials in lens design

Application of materials in lens design requires knowledge of optical properties as well as some mechanical, thermal and environmental characteristics. OPs are organic glasses that transmit well in the VIS and NIR regions. Polymer films prepared from ECC materials have been measured in the spectral area from 400 to 2500 nm by means of a UV-VIS-NIR spectrophotometer Varian Carry 5E and transmission spectra were presented in [3, 4]. All studied OPs have transmission of about 90 % in the diapason 500÷1600 nm, some weak absorption bands at 1660÷1700 nm and transmittance considerably decreases beyond 2200 nm in respect to the functional groups. At short wavelengths in VIS region fluctuations of transmittance between 75 – 85 % are registered for the different OPs. In Table 1 transmittance *TR* and the corresponding spectral range *SR* of bulk samples with 3.2 mm thickness is presented. Two SCHOTT glasses N-BK10 and N-SF57 are included for comparison. Indicated values of *TR* refer to a 10 mm thick sample in the region from 400 to 1970 nm [5]. Given spectral range is for transmittance over 70%. However, glass components are much heavier than polymer optics. For all studied OPs, measured density varies between 1.007 g/cm^3 for Zeonex E48R to 1.204 g/cm^3 for Bayer, while N-BK10 glass is with density 2.39 g/cm^3 and for N-SF57 the corresponding value is 3.53 g/cm^3.

Different measuring techniques have been used to supply sufficient refractometric data. The deviation angle method is applied to measure bulk polymer samples. We have used the Carl Zeiss Jena Pulfrich-Refractometer PR2 with its V-type SF3 glass prism to measure refractive indices (RIs) at five emission wavelengths in VIS region of the instrument’s spectral lamps with accuracy of 2×10^{-5}. A goniometric set-up was used in the entire VIS and NIR regions up to 1052 nm at eleven measuring wavelengths and obtained results are with uncertainty of 3.6 $\times10^{-4}$ [6]. Three- and four-wavelength laser microrefractometers have been applied to measure RIs of thin ECC films with an accuracy of 2×10^{-3}. The critical angle determination method is used. Selected refractive data is given in Tables 1 and 2. Studied OPs have a limited range of RI values between 1.471 for the cellulose and 1.592 for PS bulk specimens at the d-line (587.6 nm). Optical glass types are numerous and their n_d values vary from 1.49 to 1.9, but products with 1.43 and 2.1 RIs are also available. Refraction of bulk samples and thin polymer films from one and the same material at measuring wavelengths of the microrefractometers is compared in Table 2. Results of the cellulose bulk sample and film are close and RI values differ in the third decimal place, except for the shortest wavelength. Greater differences are observed for the polyacrylate polymer. For some of the measured thin films, variation of RI values with film thickness has been established [6]. These results can be explained by the fact that in case of bulk samples an average volume RI is measured, while for films a local value, near the surface, is registered. Dispersion properties of optical materials in VIS area is usually evaluated by the Abbe number at d- or e-line. Analogous number for the NIR measuring interval is introduced: $\nu_{879} = (n_{879} - 1)/(n_{703} - n_{1052})$. As seen, dispersive properties of films and bulk samples differ, which means that they should be investigated separately.

Table 1. Optical characteristics of OPs

	PMMA	Zeonex E48R	Optorez 1330	SAN	PS	Bayer	PC	N-BK10	N-SF57
n_d	1.4914	1.5309	1.5094	1.5667	1.5917	1.5857	1.5849	1.4978	1.8467
n_{879}	1.4835	1.5224	1.5021	1.5526	1.5756	1.5698	1.5683	1.4908	1.8188
$n_F - n_C$	0.0083	0.0094	0.0098	0.0160	0.0194	0.0195	0.0201	0.0074	0.0356
$n_g - n_F$	0.0052	0.0055	0.0056	0.0099	0.0115	0.0123	0.0123	0.0039	0.0221
$n_d - n_C$	0.0024	0.0027	0.0029	0.0044	0.0055	0.0054	0.0056	0.0023	0.0102
$n_s - n_t$	0.0018	0.0018	0.0030	0.0028	0.0036	0.0036	0.0036	0.0024	0.0073
ν_d	59.2	56.5	52.0	35.4	30.5	30.0	29.1	66.95	23.78
ν_{879}	96.7	100.5	71.7	66.6	55.9	54.8	54.6	83.21	41.57
$P_{g,F}$	0.626	0.585	0.571	0.619	0.593	0.631	0.612	0.5303	0.6216
$P_{d,C}$	0.289	0.287	0.296	0.275	0.283	0.277	0.279	0.3093	0.2855
$P_{s,t}$	0.217	0.203	0.307	0.175	0.186	0.185	0.179	0.3224	0.2042
TR, %	92÷95	92	93÷94	88	87÷92	88	85÷91	99.6÷98	73.3÷95.6
SR, μm	0.36÷1.6	0.36÷1.2	0.41-	0.36÷1.6	0.38÷1.6	0.38÷1.6	0.38÷1.6	0.31÷2.3	0.42÷2.0
$\Delta n/\Delta T$, $\times10^{-4}$ K^{-1}	-1.30	-1.26	-1.20	-1.10	-1.31	-1.20	-1.00	0.034	0.022
α, $\times10^{-4}$ K^{-1}	0.7	0.7	0.7	0.5	0.6	0.6	0.5	–	–
α_L, $\times10^{-4}$ K^{-1}	0.5÷0.9	0.6	0.7	0.65÷0.67	0.6÷0.8	0.65	0.6÷0.7	0.058	0.085
γ, $\times10^{-4}$ K^{-1}	-3.4	-3.0	-3.0	-2.5	-2.8	-2.6	-2.2	0.01	-0.06

Table 2. Comparative results for polymer thin films and bulk specimens

Polymer		Abbe number		Refractive index, λ, nm					
		ν_d	ν_{879}	406	532	632.8	656	910	1320
Cellulose	bulk sample	54.1	92.6	1.483	1.474	1.469	1.468	1.462	1.459
	thin film	40.9	79.6	1.493	1.473	1.467	1.466	1.460	1.457
Polyacrylate	bulk sample	63.3	97.6	1.514	1.497	1.492	1.492	1.487	1.484
	thin film	55.2	95.7	1.501	1.490	1.485	1.484	1.478	1.476

In lens design the acquired refractometric and dispersive parameters of optical materials are standardized. Except RIs and Abbe numbers at d- or e-line (546.1 nm) in correspondence to the USA and European standards, respectively, the principal dispersion $n_F - n_C$ or $n_{F'} - n_{C'}$ should be indicated. Additional characteristics as partial dispersions $n_g - n_F$, $n_d - n_C$, $n_s - n_t$ and relative partial dispersions $P_{g,F}$, $P_{d,C}$, $P_{s,t}$ are useful, too. For combination of materials in achromatic pairs relative partial dispersions should be close while the Abbe numbers differ substantially. As for example, PS or PC polymer may be combined with the PMMA material or PC with Zeonex E48R in a polymer doublet, while the N-SF57 flint and PMMA may form a hybrid glass-plastic pair. Characterization in NIR spectrum is carried out by RIs and Abbe numbers at 879 nm and partial and relative partial dispersions at s- (852.1 nm) and t-line (1014 nm). In this part of the spectrum OPs are less dispersive in comparison to VIS light and deviations of partial dispersions may be even smaller than those for glasses. OPs as PMMA and Zeonex E48R material are with lower value of $n_s - n_t$ than the N-BK10 glass, which is one of the least dispersive glasses. This is evident by the Abbe number values in NIR spectrum, too. Obviously these plastics seem to be the most suitable optical materials for night-vision optics and data communication devices.

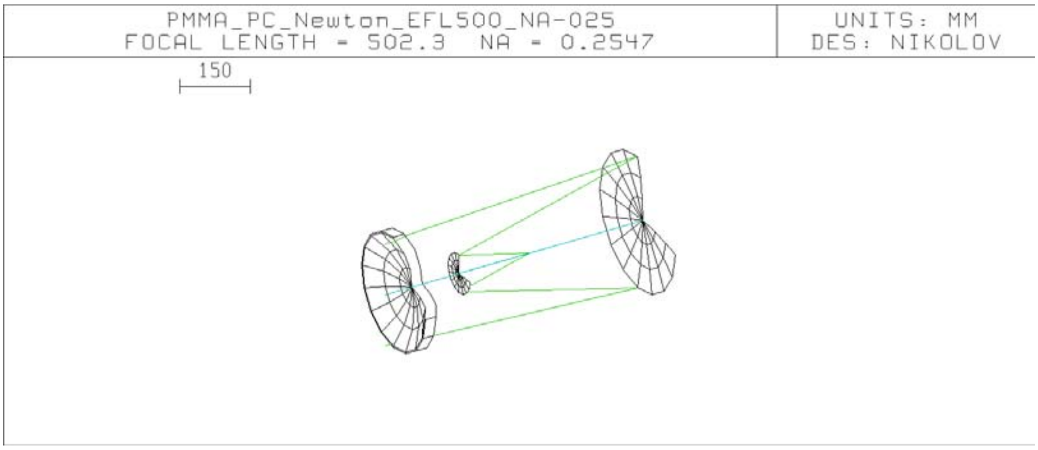
Thermal stability of OPs is very important for their practical applications in systems and devices which operate in variable or extreme environmental conditions. Heating of polymers can cause undesirable transformations in their structure and influences over optical and mechanical properties. Maximal service temperature of OPs (60 to 250 °C) is substantially less than for optical glasses (400 to 700 °C). Among all studied optical plastics, the PC material is with the highest service temperature and broadest operating temperature band –137 °C ÷ +130 °C [7, 8]. The cyclic olefin copolymer Zeonex E48R with a similar n_d as acrylic materials, provides a higher-temperature alternative. Its highest service temperature of 123 °C is about 30 °C higher than PMMA. Increase of maximal service temperature of optical systems can be achieved via introduction of suitable substituents in polymers [9] or usage of hybrid glass-polymer optics [10]. Designers of polymer optics should be aware that environmental conditions should not exceed the prescribed temperature requirements by the polymer producing companies.

One of the most important parameter in optical applications of OPs is the variation of refractive index with temperature $\Delta n/\Delta T$, which is known in literature as a thermo-optic coefficient (TOC). Its value at d-line is calculated on base of our refractometric measurements in the temperature interval 10 to 50 ^{o}C and results are presented in Table 1. Slight alterations of TOCs with wavelength and temperature are established [6]. Most stable optically polymer is again the PC material. As seen, OPs have negative values of $\Delta n/\Delta T$ in contrast to the positive thermo-optic coefficients for most of glass types. The $\left|\Delta n/\Delta T\right|$ values of plastics are with about two orders of magnitude higher than those of optical glasses. Obtained TOCs have been used to derive the linear thermal expansion coefficients α using the well-known Lorentz–Lorenz equation and then thermal glass constants γ, which represent the normalized optical power ϕ change of a thin lens to unit ϕ and unit change of T, are estimated by the relation: $\gamma = d\phi/\phi dT = (dn/dT)/(n\text{-}1) - \alpha$. Calculated γ of OPs are always negative, while for glasses positive and negative values are possible. Linear thermal expansion coefficients and absolute values of thermal glass constants are with one or two orders of magnitude greater than those of various glass types. The obtained results for α are compared to literature data α_L in the table and good coincidence is established, though the methods of estimation are completely different. Results are essential for calculation of the thermally-induced optical aberrations of polymer elements [2].

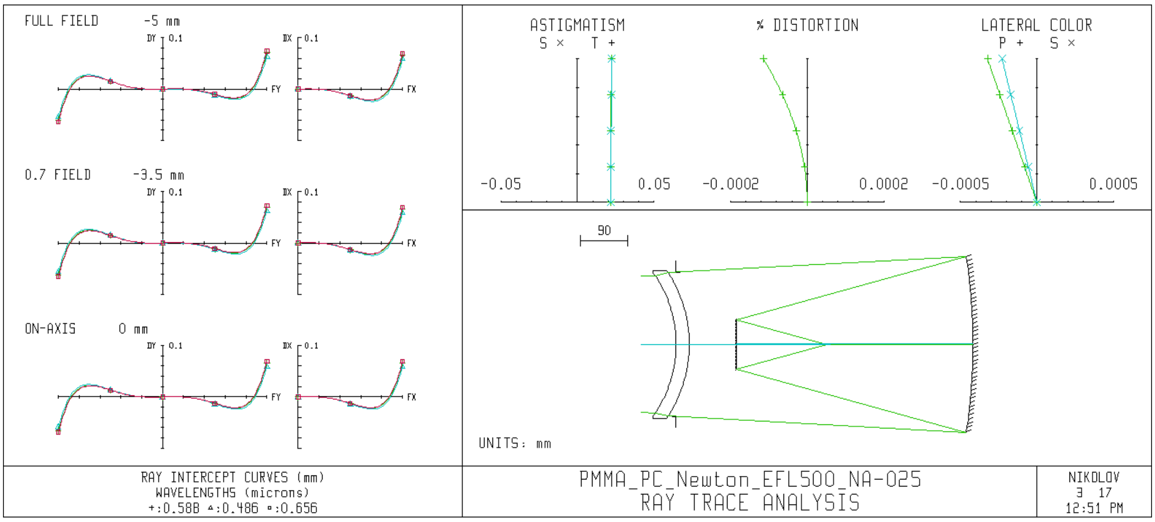
Refractometric and dispersive data of OPs are not sufficient for the proper selection of the material in lens design. Physico-mechanical properties as hardness, ultimate tensile strength, impact resistance, elastic moduli, Poisson's ratio, etc. are important, too and they have been discussed in [3].

Optical design of objective for aerospace imaging devices

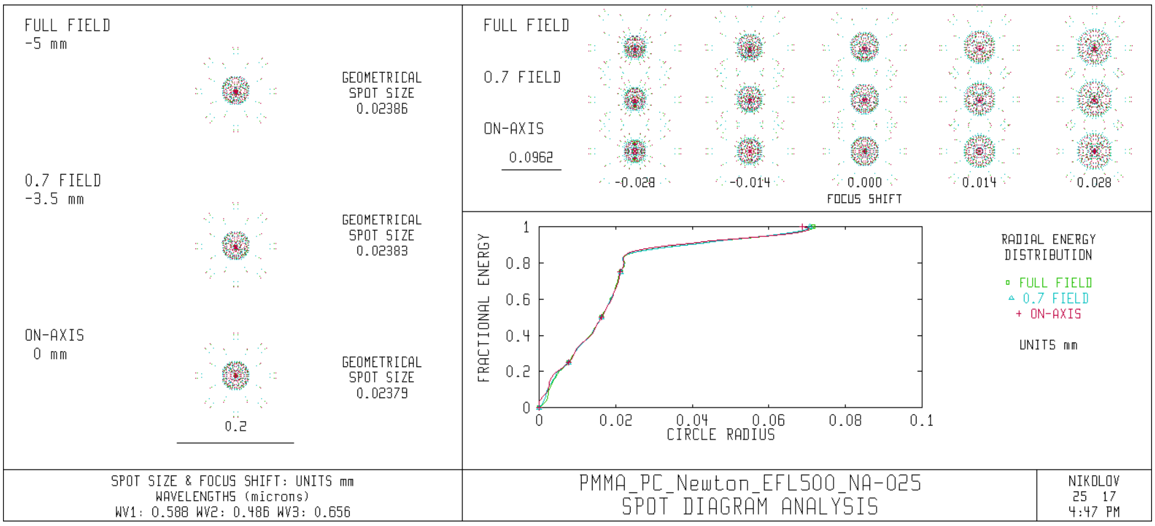
In aerospace remote imaging devices high optical performance with minimal weight of the objectives could be achieved by using polymer reflective schemes. Design of a mirror-lens Newton type objective with a 250 mm diameter is presented In Fig. 1. The system has a back focal length of 500 mm and an increased relative aperture 1:2. These parameters ensure high brightness and large concentration of energy at the focal spot of the objective. It is intended for remote imaging of ground areas contaminated with biological agents. The proposed tele-objective is focused at a distance of 5 m and object height is up to 5 mm. It consists of a PC primary spherical mirror, an achromatic PMMA meniscus lens and a secondary plane PC mirror (Fig. 1a). A slight screening effect is introduced by the second PC mirror which is compensated by the high energy spot concentration of the system. The mirrored PC elements are sputtered with aluminum reflective layers and silicon oxide anti-abrasive films are deposited over the polymer surfaces. The designed tele-objective may be used in a large spectral area which is limited only by the PMMA transmission. It is much lighter than the glass prototype and is convenient for usage in remote sensing aerospace devices.



a)



b)



c)

Fig. 1. Design of a mirror-lens Newton type objective: a) 3D optical scheme;
b) geometrical aberrations and optical layout; c) spot diagram analysis

Image quality of the synthesized optical system is evaluated by the computed geometrical aberrations and ray intercept curves at wavelengths 486, 588 and 656 nm which are presented in Fig. 1b. We have obtained a rather good sphero-chromatic correction for the designed objective. The spot diagram analysis and radial energy distribution are illustrated in Fig. 1c. The blur spot size is about 0.024 mm in the full field of view. Fractional energy concentration is slightly over 80 %. OSLO optical design software has been used.

Conclusions

OPs exhibit valuable optical, material and mechanical properties. They are transparent organic glasses in the VIS and NIR regions (Table 1). Spectral range of transmittance depends on the structure of the material and sample thickness. Comparison to optical glasses is presented. OPs have a limited range of refractive index values. Their dispersion in VIS light is higher than those of crown glasses and lower compared to dense flints. In NIR area OPs are lower dispersive and among studied polymers plastics as PMMA and Zeonex are with higher Abbe numbers than many glass types, including the widely used NBK10. Many dispersive characteristics as principal, partial and relative partial dispersions, Abbe numbers are estimated in VIS and NIR region and are useful in the design of optical polymer systems.

A drawback of OPs is their high temperature sensitivity. On the base of our refractometric measurements TOCs, linear thermal expansion coefficients and thermal glass constants are calculated (Table 1). Comparison to literature data shows good coincidence. Thermal compensation is possible in hybrid glass-plastic components and proper choice of the housing material. Combination of OPs and glasses may result in broad thermal range functionality and better correction of aberrations of optical devices. In precise imaging devices, glass components carry the optical power while polymers, usually as a layer over the glass, are used for reproducing unique geometrical surfaces to take advantage of the inherent quality and consistency of plastic moulding. Some differences in refraction and dispersion of polymer films are established in comparison to bulk samples (Table 2).

Design of an all-plastic Newton-type objective (Fig. 1), intended for remote imaging applications,is accomplished on base of optical and material characteristics of studied OPs. The system is with low weight, increased impact resistance and well corrected sphero-chromatism. Presented example of optical design illustrates that application of OPs is not a restriction on image quality of polymer optics.

References:

1. Lytle, J. Polymeric optics, in Handbook of Optics, Vol. II, Ed. Bass M. et al., McGraw - Hill Inc., New York, 1995, pp. 34.1-34.21.
2. Nikolov, I., S. Kasarova, N. Sultanova. Some aerospace applications of optical polymers. Aerospace Research in Bulgaria, Vol. 26, 2014, pp. 220-242.
3. Nikolov, I., S. Kasarova, N. Sultanova. Optical and material characterization of polymer materials and samples. SES 2014 Proceedings, 2015, pp. 473-478.
4. Nikolov, I., S. Kasarova, N. Sultanova. Polymer materials for NIR and laser applications. SES 2013 Proceedings, 2014, pp. 475-480.
5. SCHOTT Glass Technologies. http://www.us.schott.com, 2017.
6. Sultanova, N., S. Kasarova, I. Nikolov. Refractive Index Metrology of Optical Polymers, Lap Lambert Academic Publishing, Saarbrücken, ISBN: 978-3-659-55714-9, 2014.
7. Nikolov, I., Z. Zaharieva. Mirror-lens optical system for image spectroscopy device, Proceedings of SPIE, Vol. 3573,1998, pp. 413-416.
8. Nikolov, I., A. Krumov, Z. Zaharieva. Optical lens assembly for image spectrometry. Balkan Physics Letters, Vol. 13, 2001, pp. 135 – 141.
9. Driessen, A, A. Leinse, S. Musa, R. M. de Ridder, Sulur. Polymer-based integrated optics devices, in Polymer Optical Fibers; Ed. H. Nalwa, American Scientific Publishers: Stevenson Ranch, CA, 2004, pp. 73-101.
10. Sultanova, N., S. Kasarova, I. Nikolov. Characterization of optical properties of optical polymers. Optical and Quantum Electronics, Vol. 45, No.3, 2013, pp.221-232.