OPTICAL REVIEW Vol. 20, No. 5 (2013) 355–360

Invited Review Paper

Hybrid Miniature Objectives Using Freeform and Binary Surfaces for Digital Applications

Irina LIVSHITS and Vladimir VASILYEV

Lab of CAD for Opto-Information and Energy Saving Systems, NRU ITMO, Saint Petersburg, Russian Federation

(Received May 15, 2013; Accepted June 14, 2013)

An attempt to show one of the approaches for starting hybrid miniature objectives using freeform and binary surfaces is presented. An example for a wide-angle objective with DOE is given.

Keywords: optical design, abberations, digital camera, hybrid objective, freeform, binary surfaces

1. Introduction

In the market for objectives for digital applications (mobile phones, photographic cameras, machine vision, optical sensors, etc.) there exist many good optical systems, which are successfully used for their purpose. Constant and strong tendencies to increase the resolution of such objectives and decrease its size and number of elements require new ideas to solve the mentioned problems.

As is known from the theory of optical design, to achieve better image quality (higher resolution) we need more parameters (constraints) to operate. One has to understand that some constraints will be "tied" — they are used to decrease the size of the objective (keep it as small as possible). It is important to understand that two requirements, image quality and small size of the lens, are always in contradiction with each other and it is not easy to find a good optical system that satisfies these two requirements simultaneously.

The use of only traditional refracting and reflecting surfaces, even with aspheric shape, is insufficient to achieve further progress. This is why optical designers are always looking for new solutions which can deliver more parameters for the optical system.

In optical design, both theory and engineering are always connected with fabrication. So, if we want to achieve compact design with high resolution we need improvements in both optical design and fabrication. Improvement in optical design also requires developments in optical design software and improvements in fabrication, that is, new fabrication and testing tools.

The fast development of science and technology has recently offered a technological opportunity to produce freeform and diffraction surfaces, which are very promising for solving the contradiction mentioned above. Both of these surfaces were known long ago, but only now are optical designers starting to use them more actively, because it has become possible to make them!

The literature devoted to this subject offers a new name for combined refractive–diffractive surfaces: the "hybrid" lens. Some examples of hybrid optical systems can be found in Refs. 1–5.

We propose to widen the term "hybrid" by also applying it to objectives with freeform surfaces.[6] Both of these types of surfaces have very recently become available in production, and they both give the optical designer the necessary constraints to achieve the goal of compact and high quality objectives.

As we are working in a university and an important goal is to explain design principles to students, we aim to present a logical approach to this design.

2. Requirements for Lenses Used for Digital Applications

As we explain to our students, there are only a few special requirements for lenses used for digital applications, but they are very important:

1. Image-space telecentric design (because silicon-based digital image sensors accept light best when it lands squarely on the sensor rather than at an angle of certain amount);
2. Uniform image quality for the entire image plane, from the axial point to the edge of the lens;
3. Compact construction;
4. Ability to be mass produced while keeping the high quality of the lens.

Some attempts to use regular lenses for digital applications which add a set of micro-lenses into the optical system just in front of the sensors can help alleviate this by making the optimal chief ray angle vary across the field.

The most popular sizes of the image matrix are presented in Table 1; more details can be found in Ref. 7. Again we find a contradiction between image quality and the size of the lens: a bigger matrix requires a bigger lens and more constraints to correct aberrations.

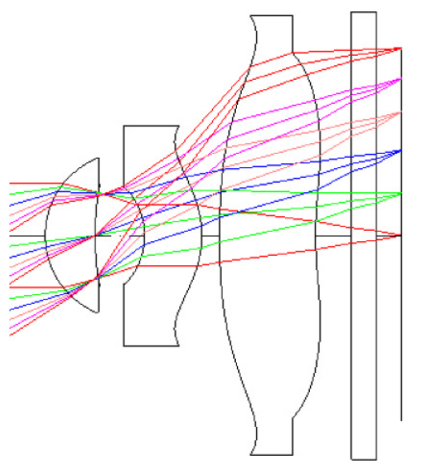
An example of an objective for a mobile phone camera for 5 M pxls is presented in Fig. 1. All lenses are plastic and all surfaces are high order aspheric. The lens has almost diffraction-limited image quality, which means that aberrations are so well corrected that they are limited by diffraction only. Recently we started to design a mobile phone lens with a binary lens, and according to preliminary estimation we hope to obtain two lenses and a plate with diffraction coating.

3. Freeform Surfaces

Therefore, many optical designers have started using freeform surfaces. The most popular applications for them

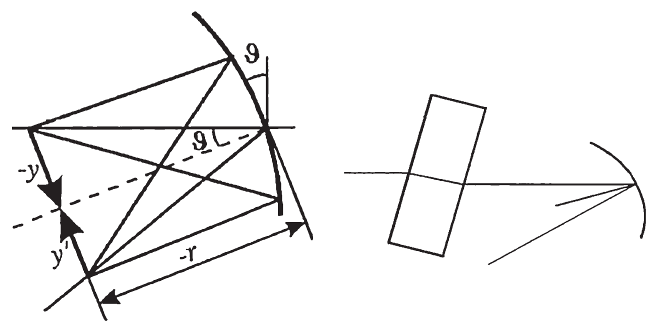
Table 1. Image matrix size.

Format	Size in mm	Square mm^2	Camera
35 mm "full frame"	36 × 24	864	Blur frame
APS-H	28.7 × 19	548	Canon
APS-S	23.6 × 15.7	370	Nikon DX, Pentax, Sony
APS-C	22.2 × 14.8	329	Canon
Foveon	20.7 × 13.8	286	Sigma
4/3″	17.3 × 13	225	Nikon 1/CX
1″	13.2 × 8.8	116	
1/1.7″	7.6 × 5.7	43	
1/1.8″	7.18 × 5.32	38	
1/2.5″	5.76 × 4.29	25	



		Technical	General
F-number	J	F2	1
Field angle	W	2w=65	2
Focal length	F	4 mm	2
Spectral range	L	visual	1
Image Quality	Q	Diffract	2
Back focal length	S	1	2
Entrance pupil	D	inside	0

Fig. 1. (Color online) Optical scheme of objective for mobile camera lens and its technical and general specifications.[8,29]



(a) (b)

Fig. 2. A tilted mirror when the object and image plane coincide — used as the basic element (a); a tilted correction element — a plane-parallel plate — compensates for tilted astigmatism and does not introduce other aberrations (b). $-y$, object height; y', image height; $-r$, radius of curvature of a mirror; ϑ, angle of tilt for a mirror with respect to the centred ray. $\vartheta = y/r$.

are ophthalmology (lenses) and head-up displays (mirrors), and we aim to expand their applications for use in digital cameras, first of all by making them more compact.

"Freeform surfaces are defined as any non-rotationally symmetric surface or a symmetric surface that is rotated about any axis that is not its axis of symmetry".[9)]

Kevin Thompson called it "a revolution in imaging optical design":[10)] "A revolutionary optical surface is the result of developments in the theory of aberrations, techniques in optical system optimization, computation speed, precision fabrication of surface without symmetry, and extensions to the range of the surface slopes allowed in optical testing".

It is almost unknown that in Russia it was Lomonosov who first had the idea of using the first freeform surfaces, which he proposed in 1748 to decline a spherical mirror to avoid an obscuration.[11)]

In Russia freeform surface modifications have been used since the 1970s by Professor Russinov,[11)] who called them "decentred" optical systems (Figs. 2, 4, and 5). He often used a combination of refractive and reflective elements; some of them were decentred and/or tilted and often they had aspheric shape. He designed strange-looking optical systems, for example those shown in Figs. 6 and 7, for different purposes, including photographic lenses.

A positive property of reflective surfaces is that they are free from any chromatic aberrations and have much bigger values of their radii of curvature compared with the radii of refractive surfaces with the same optical power for optical material with a relatively low refractive index.

The main idea for starting such system is to use a basic element (which provides the optical power of the system) and corrective elements which correct residual aberrations of the basic element.

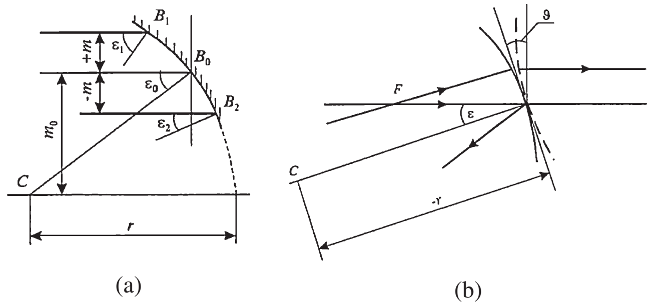


Fig. 3. Telecentric pass of a chief ray: real ray (a) and ray scheme — transfer mirror system into a lens system (b).

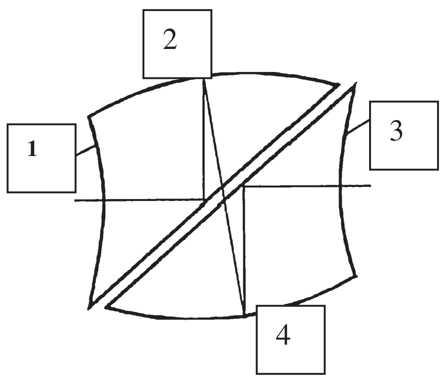


Fig. 4. Relay system from two mirror-lens "confocal" components. Note that "confocal" means that the surface is concentric to the focal point, so a marginal ray travels normal to this surface and does not have any aberrations. Surfaces 1 and 3 are confocal; Surfaces 2 and 4 are working as a TIR.

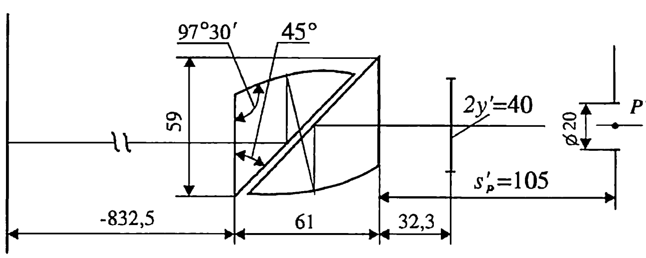


Fig. 5. Example of a projection lens from "sphero-prizmatic" elements; $V = -10x$ (shown as a reversed system).

The main aberrations of decentred and tilted elements are aberrations of the chief ray — astigmatism and distortion.

It seems obvious that correction elements to correct decentred aberrations also have to be decentred.

Next figures, Figs. 3–7, show raytracing of mirror system, transformation mirror system to a lens system with a few examples.

Using monolithic lens Russar-mono (Fig. 6) it is possible to receive pictures of satisfactory quality. One feature of this lens is the probability of some flare of the image. This does not happen if to use the objective as a projection system.

A design environment to support optical designers willing to design freeform surfaces is presented in Ref. 28.

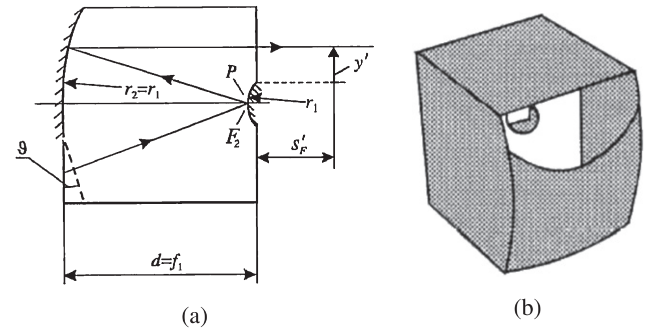


Fig. 6. Russar-mono: Two-mirrors — refractive objective with telecentric chief rays passing in the image space and its general view of the objective Russar-mono: $f' = 50$ mm, F3.5; $2w = 30°$.

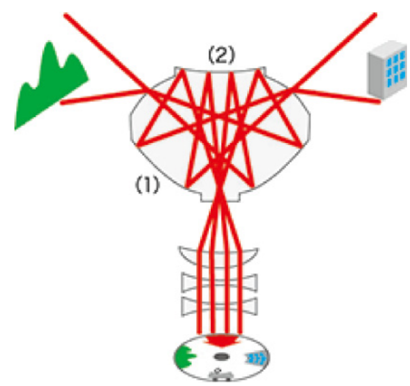


Fig. 7. (Color online) A 360° lens, axisymmetrical free-form.[28]

4. Binary (Diffractive) Surfaces

Hybrid diffractive–refractive lenses are used in various optical systems to diminish chromatic aberration.[1–5,14–21,24–26] This method is based on the utilization of the physical phenomenon whereby a refractive surface and a diffractive surface in an optical system cause the behaviour of chromatic aberration with respect to a ray of light of a certain reference wavelength to occur in respective opposite directions. One can expect to compensate a chromatic aberration by using a diffractive surface in a system of lenses made from the same glass type instead of using lenses made of different optical materials. In most of the existing systems the lenses are made from different materials including plastics (fabrication of the diffractive structure in plastic is easier). Usually these systems include aspheric surfaces (Figs. 8 and 9).

An interesting property of the diffractive lens is that the field curvature in all cases is zero, and in the approximation of a large index of refraction the distortion remains zero.[11) That is why the use of diffraction lenses in wide angle objectives looks promising.

Imaging wide angle lenses are required for many applications. New emerging applications include rear-view cameras for cars and interior monitoring cameras for buses and aeroplanes.

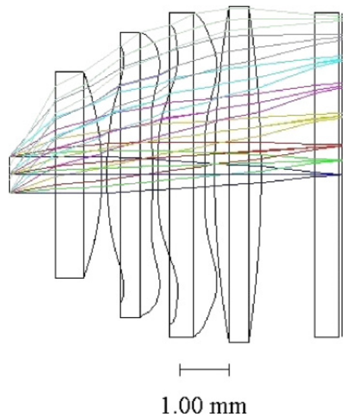


Fig. 8. (Color online) Wide angle refractive objective with aspheric surfaces for a digital camera.[8,27)]

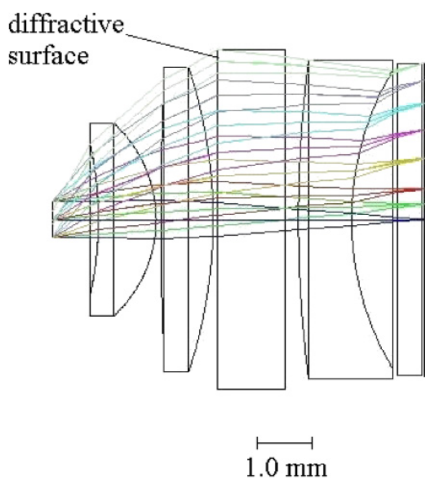


Fig. 9. (Color online) Wide angle hybrid diffractive–refractive camera lens.

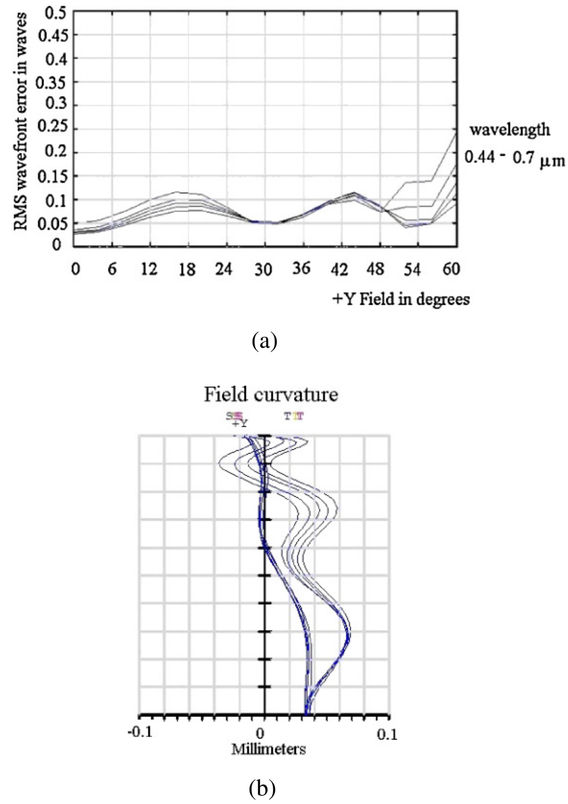


Fig. 10. (Color online) Computer-generated image quality characteristics of the camera lens shown in Fig. 8: wavefront error (a) and field curvature (b).

Conventional designs of wide angle lenses tend to have a significant amount of optical distortion. There is also a need for small size and low weight for many emerging applications. The image quality of the lens must also be high for compatibility with megapixel digital cameras.

Most lens assemblies providing the performance requirements of a wide angle and high image quality are large, heavy, and expensive to produce because of the large number of elements used. The number of lens elements in such lens assemblies usually varies from eight to twelve.

In the use of aspheric surfaces of complicated form, having a large number of high order coefficients helps to reduce the number of elements to four. However, the fabrication and control of these surfaces with rather high accuracy for all the coefficients may be complicated and expensive.

It is already common to use diffractive optical elements to control the wavefront formed by aspheric components. This looks reasonable for mass production; however, when only a small number of equal aspheric lenses or only one lens is to be fabricated, the design and fabrication of a special control diffractive element for each case will significantly increase the cost of an aspheric lens.

One of the advantages of diffractive lenses is that they can be directly controlled, and in some cases this makes the substitution of the aspheric surfaces by diffractive ones reasonable.

4.1 Example: wide-angle camera lens

The starting point for this design was the refractive wide angle camera lens shown in Fig. 8 with four aspheric surfaces. This lens has a field angle of 110°, F5, works with a CCD matrix of 1/3″, and requires a small entrance pupil diameter (like a hidden camera — it is often called a "pinhole" lens). The specific feature of this kind of objective is very high distortion, which can be partially compensated by the use of rather complicated aspheric optics.

The image quality characteristics of this camera are shown in Fig. 10, where Fig. 10(a) shows the RMS wavefront errors and Fig. 10(b) the field curvature. The field curvature plot illustrates the distance from the real image surface to the paraxial image surface as a function of the field coordinate. The tangential data are the distances measured along the Z-axis from the image surface to the paraxial image surface measured in the tangential (YZ) plane. The sagittal data are the distances measured in the plane orthogonal to the tangential plane.

(a)

(b)

Fig. 11. (Color online) Computer-simulated image of the same scene produced by the camera with the aspheric lenses (a) and the camera with the hybrid diffractive–refractive lens (b).

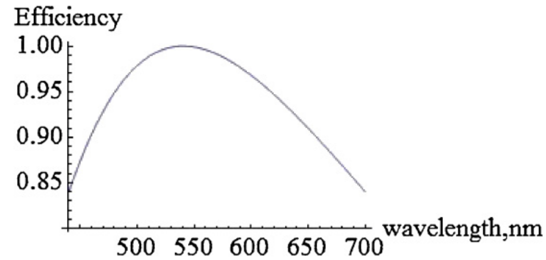
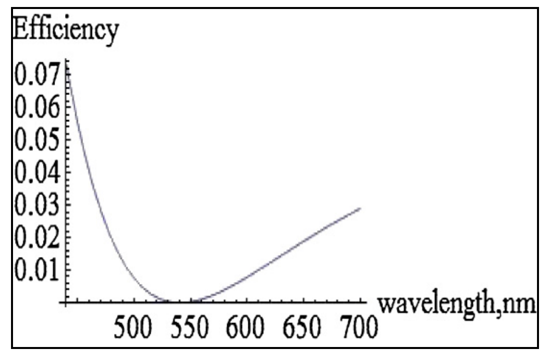
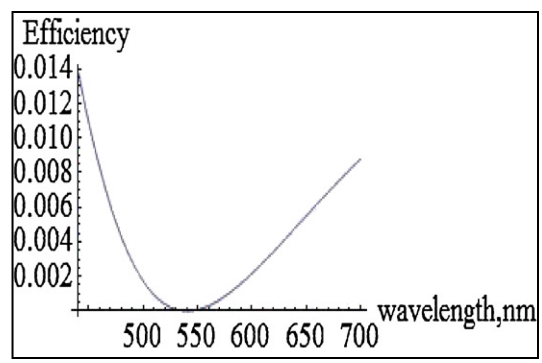


Fig. 12. (Color online) The diffraction efficiency of the diffractive lens used in the objective in Fig. 9.



(a)



(b)

Fig. 13. (Color online) The diffraction efficiency of the diffractive lens used in the objective in Fig. 9 in the second diffraction order (a) and third diffraction order (b).

The design process started by reducing the number of aspheric coefficients and optimizing the other parameters. At some stage when it began to be difficult to trace rays from the wide field points through the system, the diffractive structure was placed on one of the lens surfaces. At the end of the optimization process the surface with a diffractive structure became flat and all other lens surfaces began to be spherical. The optical scheme of this hybrid system is shown in Fig. 9.

The objective of the camera with the hybrid lens has an RMS wavefront error about 10 times smaller than that of a camera with aspheric surfaces. The difference in the distortion and the field curvature of the diffractive and the aspheric variants is not so big.

Computer-simulated images of the same scene produced by these two camera lenses are shown in Fig. 11(a) for the aspheric variant and Fig. 11(b) for the diffractive variant. The image produced by the camera with the hybrid diffractive-refractive lens at least does not look worse than the image produced by the camera with aspheric lenses.

The simulation whose results are shown in Fig. 11 considers only the ray tracing through the camera. The diffraction efficiency of the diffractive lens is shown in Fig. 12. The disadvantage of this design is that it is possible for stray light to occur due to the nonzero efficiency of higher diffractive orders.

A complete ghost analysis is beyond the scope of this work. The diffraction efficiencies for the second and third orders are shown in Figs. 13(a) and 13(b). For the fourth order the efficiency is less than 0.5%, and for the higher orders it is practically negligible.

In the case when the image quality was optimized only for the first order, the sharpness of the image decreases with increases in the order.

The image simulation result for the second diffraction order for the current lens is shown in Fig. 14. The potential solution of this problem may be in the differential optimization of the image quality for more than one order for the edges of the spectral region.

Fig. 14. (Color online) Computer-simulated image for the second diffractive order for the camera with the hybrid diffractive–refractive lens.

5. Conclusions

1. For applications of the hybrid freeform diffractive–refractive optical systems considered in this paper, the imaging characteristics are at least not worse and are in some points even better than for the pure refractive prototypes. The parameters of the hybrid diffractive–refractive lens for the wide-angle camera lens are similar to the parameters of the hybrid diffractive–refractive lens, but the lens construction is much simpler.
2. The next goal is further development of system optimization for hybrid objectives.
3. When the suppression of the high diffraction orders is important for the wide angle camera lens, it should be taken into account at the stage of the detailed lens profile design related to one or another fabrication technology. The alternative way to solve this by increasing the image sharpness for more than one order can be a topic of the next study.

References

1) T. R. M. Sales and G. M. Morris: Appl. Opt. **36** (1997) 253.
2) T. Stone and N. George: Appl. Opt. **27** (1988) 2960.
3) R. Brunner, R. Steiner, K. Rudolf, and H.-J. Dobschal: Proc. SPIE **5177** (2003) 9.
4) R. Brunner, R. Steiner, H.-J. Dobschal, D. Martin, M. Burkhardt, and M. Helgert: Proc. SPIE **5183** (2003) 47.
5) H. J. Dobschal: EOS Top. Meet. Diffractive Optics, 2007, p. 84.
6) Y. Arieli, S. Ozeri, N. Eisenberg, and S. Noach: Opt. Lett. **23** (1998) 823.
7) Web [http://en.wikipedia.org/wiki/File:SensorSizes.svg].
8) I. L. Livshits et al.: Large-aperture wide-angle lens. Patent for useful model N 80248 (13) U1 (51) MIIK G02B9/14 (2008).
9) Web [www.pec.edu/faculty_staff/garrard/spie5874_10.pdf].
10) J. Rolland and K. Thompson: SPIE Newsroom (July 2012) [DOI: 10.1117/2.1201207.004309].
11) M. M. Rusinov: *Composition of Noncentered Systems* (State University Press, Saint Petersburg, 1995r) p. 195.
12) G. W. Forbes: Opt. Express **20** (2012) 2483.
13) O. Cakmakci, K. Thompson, P. Vallee, J. Cote, and J. P. Rolland: Proc. SPIE **7618** (2010) 761803.
14) D. Mund and K. M. Hammerl: Patent Application Publication WO 2005 121 842 A1.
15) G. J. Swanson and M. Scott: US Patent 5442480 (1995).
16) M. H. Kreitzer: US Patent 6529336 (2003).
17) H. Ogawa: US Patent 6825979 (2004).
18) Y.-C. Huang: US Patent 6741403 (2004).
19) Y.-C. Huang: US Patent 6490102 (2002).
20) K. Maruyama: US Patent 6101035 (2000).
21) D. C. O'Shea, T. J. Suleski, A. D. Kathman, and D. W. Prather: *Diffraction Optics Design, Fabrication and Test* (SPIE, Bellingham, WA, 2004).
22) ZEMAX Optical Design Program User's Manual (10 May 2012).
23) CODEV Training Notes (Aahen, Germany, 2002).
24) V. I. Kalikmanov and E. A. Sokolova: J. Opt. Soc. Am. **23** (2006) 497.
25) D. W. Sweeney and G. E. Sommargren: Appl. Opt. **34** (1995) 2469.
26) D. Faklis and G. M. Morris: Appl. Opt. **34** (1995) 2462.
27) I. G. Bronshtein et al.: Russian Patent N 84590, priority from 10.03.09.
28) Web [http://web-japan.org/kidsweb/hitech/360-degree/003/html].
29) CODEV Optical Design Program User's Manual (January 2013).