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LIGHT EFFICIENCY OF LED ROAD LUMINAIRES WITH FLAT GLASS

Hristo Vasilev, Vultchan Gueorgiev, Iva Draganova

Abstract: *The application of LEDs in the street lighting offers many opportunities but requires development of new optical systems. The designers are tempted to achieve as wide light distribution curves as possible increasing that way the efficiency of luminaires being developed. This is achieved by spatial distribution of LEDs and /or by adding secondary optics – reflective or refractive. Often the expected benefits are estimated only based on analysis of secondary optics, disregarding additional components comprising the entire luminaire. The influence of internal reflection of the luminaire protective glass on the light distribution curve and lighting efficiency are discussed here. The internal reflection acts in a way that eliminates the benefits of very wide light distribution. The impacts of that phenomenon on the light distribution curve of the entire luminaire and on the quantitative indices of the road lighting are studied.*

The LEDs (Light Emitting Diodes) without any doubt are the light source of the future. Some years ago LED with white light and luminous efficacy of 130 lm/W appeared on the market and this year Cree Company produced LED which with consumption of one watt produces luminous flux of 160 lm. This makes the LEDs the most efficient light source in the moment, which is a presumption for their fast penetration in all lighting applications.

The intensive development, the great number of LED modifications and the lack of experience and routine define the main problems in design and construction of LED luminaires [3, 5, 6]. The LED light sources differ from the conventional ones with their luminous and maintenance characteristics and the conceptions, applied for construction of luminaires with conventional light sources are not applicable for construction of LED luminaires.

The main differences with the conventional lamps are the heat and light emission of the LEDs. The LEDs are point sources that emit light in the lower hemisphere, unlike the discharge lamps that are considered as a light source with circular-symmetric radiation. The classical incandescent and discharge lamps emit heat basically through irradiance, while the LEDs emit low potential heat (with low temperature), which makes the irradiation impossible. This is the reason why the main challenges in front of the constructors of LED luminaires are to ensure normal temperature conditions and the desired light distribution when using LED light sources.

There are a lot of publications, especially from earlier years, in which the fact that the LED is a point light source is considered as one of their main advantages. Actually this is a distinctive feature that makes them different from the conventional sources and namely the discharge and incandescent lamps. This feature of the LEDs leads to the task for design of optimal optical system of luminaires working with LEDs as light sources [1, 2].

In the current publication, a less discussed in the literature problem is examined and namely the influence of the optical properties of the diffuser of the luminaire on its luminous efficacy [8].

Optimal light distribution curve for street lighting

In the field of street lighting, based on a lot of investigations, the parameters of the optimal light distribution curve are established, especially for standard lighting arrangement, where the luminaires are mounted on poles above the illuminated streets. It is considered that the light distribution curve have to be wide with maximum intensity in the C15 plane and $\gamma > 65^o$.

At the moment a lot of constructions are developed and the main efforts are in two directions – refractive optical systems (with lenses) and reflective optical systems. In both cases, the aim of the constructors is to save the inverse problem and to synthesize such an optical system that will convert the light distribution of the LED light source (or sources) in to the known optimal light distribution – fig. 1. This problem is extremely hard and cannot be considered as decided. N most of the cases the problem is transformed to will to widen the derivative light distribution as much as possible. There is even catalogue data about luminaires with light distribution curves that have very big angle of maximum intensity – about 70^o and more. Such angles are practically achievable, but here comes the question about their lighting and economic efficiency

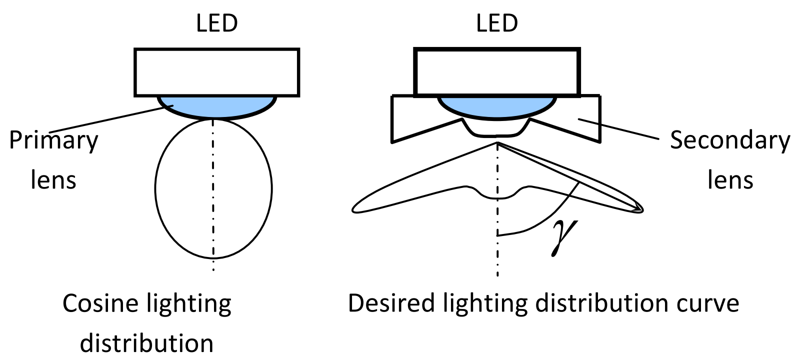


Fig. 1 The convertion from “natural” lighting distribution of LED to the desired lighting distribution of the luminaire is the main lighting task

When designing new optical systems, the efforts are directed only to the primary optics – lens or reflector and a lot of factors, considered as minor are neglected. In this way it is possible constructors, aiming to achieve as wide curve as possible to come out with a technical decision that have bad parameters when it is actually realized.

In the classical luminaires it is compulsory to use protective glass, which separates the light source from its environment. It plays the role of refractor of the luminaire. In the street lighting there are strict requirements for the degree of protection (at least IP54, and IP 65 is recommended), which means that this situation will be preserved for the LED luminaires i.e. they cannot count only on lenses, but also need protective glass to keep them from dust and moisture. The light from the LEDs, refracted at a sudden angle from the lenses or the reflector of the primary optical system, have to pass through the protective glass, where part of it is absorbed, part is transmitted and part is reflected.

Only the absorption coefficient can be considered constant, it does not depend on the light distribution and is about 1% for 1mm of enlightened glass (1mm of enlightened glass with thickness of 1 mm will absorb 1% of the light falling on it).The typical thickness of the protective glass is 4mm and besides this in order to decrease the price instead of enlightened glass, tempered glass is used with normal optical properties, which makes the absorption coefficient change in the range of 4 to 6 %. The use of alternative materials PMMA, plexiglass and so on is not common not only because of the bad transmission coefficient, but also because of other drawbacks they have like change of the color and instability to the abrasive action of the street dust.

Refraction and reflection of light

The refraction and reflection of light on the boundary of two plane surfaces (fig.2) depends on the polarization of light and is described by Fresnel equations:

$$R_s = \left(\frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t} \right)^2 = \left[\frac{n_1 \cos\theta_i - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i \right)^2}}{n_1 \cos\theta_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i \right)^2}} \right]^2$$

$$R_p = \left(\frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i} \right)^2 = \left[\frac{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i \right)^2} - n_2 \cos\theta_i}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i \right)^2} + n_2 \cos\theta_i} \right]^2$$

Here Rs, Rp are coefficients of perpendicular and parallel polarization and are represented by means of ratio of the power of reflected and fallen luminous flux. According to the energy conservation law, the transmission coefficients will be calculated by the formulas:

$$\tau_s = 1 - Rs$$
$$\tau_p = 1 - Rp$$

When the falling light is not polarized, the integral reflection coefficient and transmission can be calculated as follows:

$$R = \frac{R_s + R_p}{2}$$

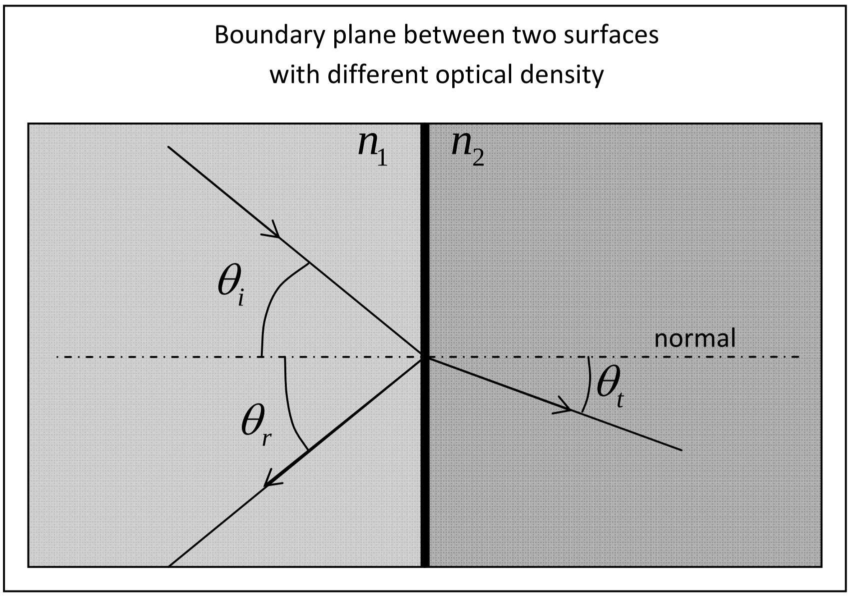


Fig. 2 Falling, refracted and reflected beams

For the case when the boundary air-glass is taken in consideration (n_{air} =1, n_{glass}=1.5), the integral coefficients of refraction and reflection are shown on fig. 3. It is obvious that with the increase of the angle, under which the light falls on the boundary surface, the quantity of the transmitted light decreases. This influences directly the optical efficiency of the luminaire and can make it inefficient.

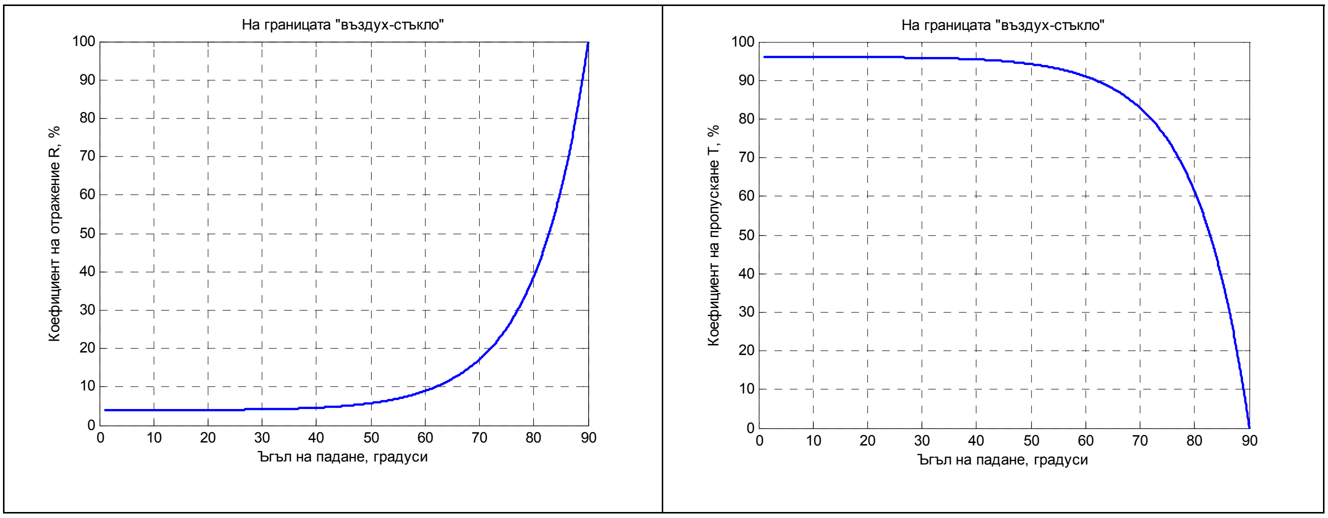


Fig. 3 Transmission R and reflection τ coefficients on the boundary air – glass

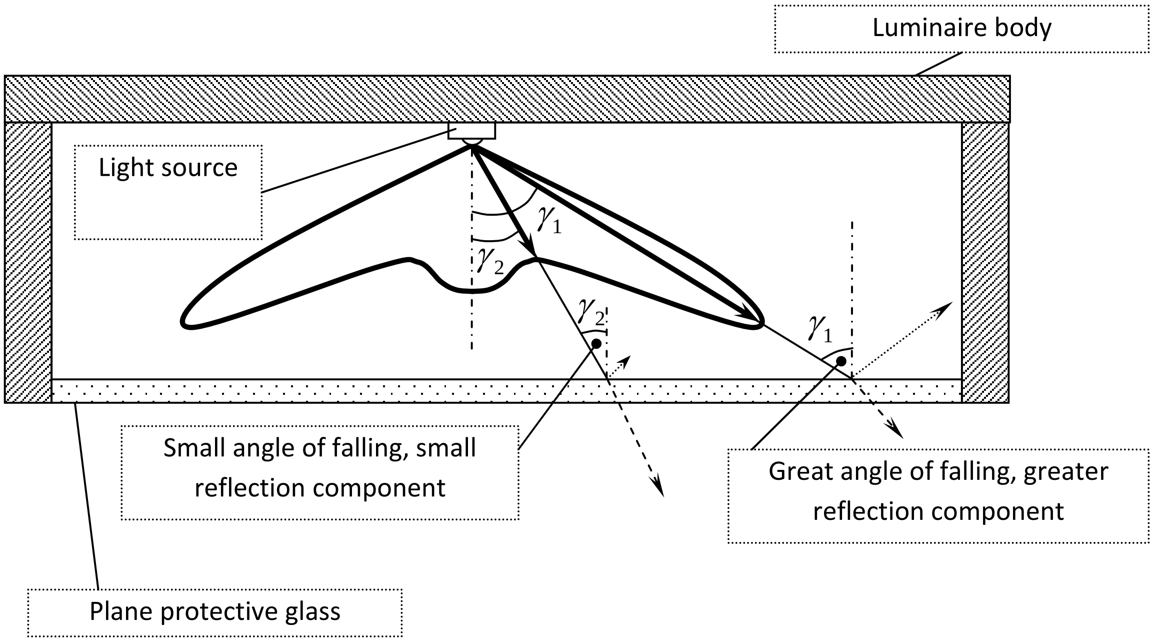


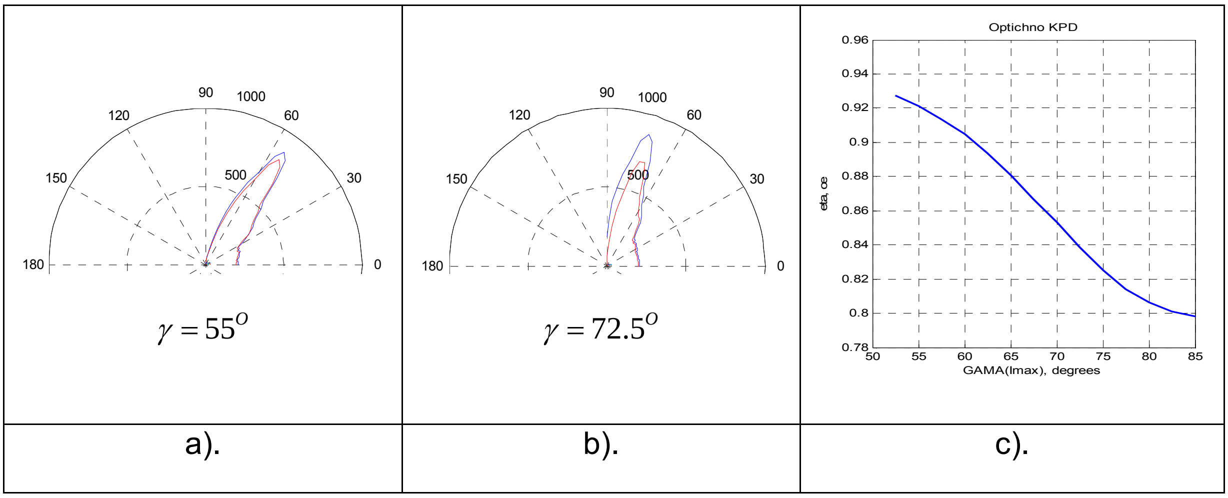
Fig. 4 Inner reflection effect in the plane protective glass of a luminaire

When estimating the efficiency of an optical system, it is necessary to take into account not only the influence of the lenses or the reflector, but also the influence of the protective glass, because it can change noticeably the efficiency of the luminaire as a whole, due to the inner reflection and the decreased transmission coefficient [7,8]. The effect gets stronger with the widening of the light distribution curve. When the maximum intensity angles are noticeably big – above 67^{o}, an efficient luminaire can be achieved only through convex protective glass that eliminates the above mentioned effects.

Influence of the inner reflection on the light distribution curve

The influence of the above mentioned effect on the light distribution curve and the optical efficiency for a definite case is shown on fig. 5. When the angle of the maximum intensity of the light distribution curve is not big (fig. 5 – a), the reflection losses in the plane protective glass are not big and the light distribution curves for the case of luminaire with or without protective glass are almost the same. With the increase of the angle of maximum intensity, however, a greater part of the flux of the source falls on the plane glass at an angle at which the reflection coefficient has a great value and part of the luminous flux does not leave the luminaire but remains inside it because of that. The results shown on fig. 5 are obtained neglecting the multiple reflections, i.e. the reflected from the plane glass light is considered as lost. The last figure (fig. 5 – c) shows the relative decrease of the luminous flux, leaving the luminaire that is due to the inner reflection. On the y – axis stays the ratio between the luminous flux of the luminaire, when plane protective glass is used and the luminous flux of a luminaire without protective glass. On the x – axis stays the angle of maximum intensity.

The curve is obtained through calculations, changing the maximum intensity angle, but keeping the luminous flux constant in the case without glass.



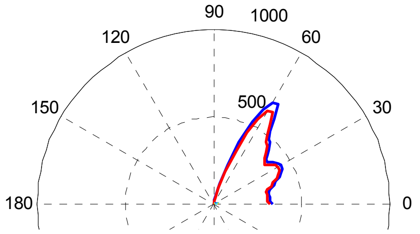
Фиг. 5. Light distribution curves for the case with and without protective glass shown in the same coordinate system – a) at angle of maximum intensity-55^{o}, b) at angle of maximum intensity 72.5^{o}, c) graphical results about the ratio between the luminous output of the luminaire with and without protective glass for different angles of maximum intensity

The next figure shows light distribution curves, where the maximum intensity is significantly increased at constant luminous flux. At the same coordinate system are shown the curves as they would be with and without plane protective glass. A 7m wide street with distance between poles 30m and mounting height of the luminaires 7m is considered. At this geometry the basic photometric indicators of the lighting system are calculated, using luminaires with the light distribution curves shown. The calculation are made assuming a luminaire with and without protective glass. For the photometrical calculations the following street geometry is assumed – width B=7m, distance between two poles S=30m, height of poles H=8m, boom length OH=1 m.

Analogic results showing the dependence between the photometric indicators and the angle of maximum intensity at different geometries of the lighting system are shown on the following figures. The dashed line shows the cases when the plane protective glass is not taken into account and the solid line stands for the case when the light losses in the protective glass are considered. The x – axis stays for the maximum intensity angle in C15plane. In all the cases the luminous flux of the luminaire is considered constant.

As it can be seen from fig. 7, when the inner reflection effect due to the plain glass is not considered, it can be assumed that with the increase of maximum intensity angle γ 70^{o}, the luminance of the road also increases. Because the maximum intensity is in C15 plane, with the increase of γ above this value, a great part of the luminous flux exits the boundaries of the road and the luminance decrease.

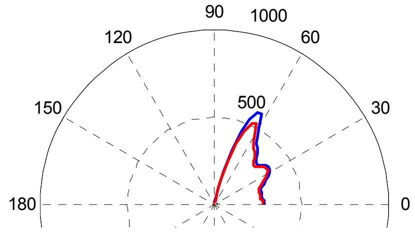
$$\gamma_{\max} = 57.5^{O}$$



	Lav cd/m2	Eav lx	Uo	Ul
With glass	0.43	6.9	0.17	0.33
Without glass	0.46	7,3	0.17	0.33

$$\frac{\Phi_{without\ glass}}{\Phi_{with\ glass}} = 0.93$$

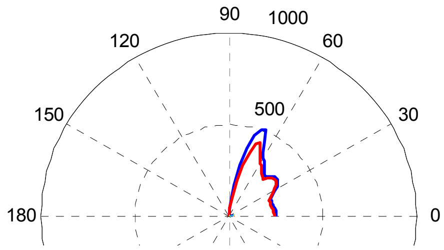
$$\gamma_{\max} = 62.5^{O}$$



	Lav cd/m2	Eav lx	Uo	Ul
With glass	0.43	6,4	0.25	0.54
Without glass	0.48	6,8	0.26	0.52

$$\frac{\Phi_{without\ glass}}{\Phi_{with\ glass}} = 0.92$$

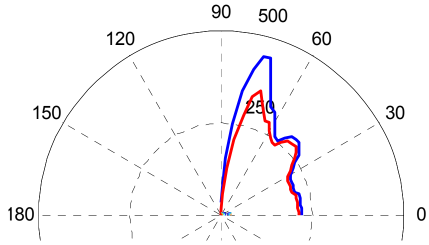
$$\gamma_{\max} = 67.5^{O}$$



	Lav cd/m^2	Eav lx	Uo	Ul
With glass	0.42	5.7	0.34	0.81
Without glass	0.49	6,1	0.35	0.79

$$\frac{\Phi_{without\ glass}}{\Phi_{with\ glass}} = 0.90$$

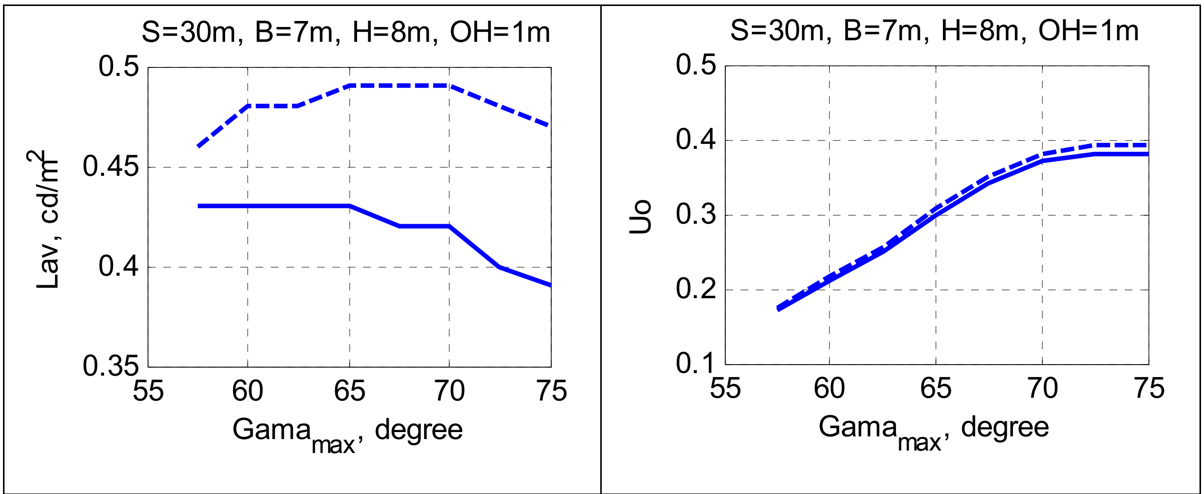
$$\gamma_{\max} = 72.5^{O}$$



	Lav cd/m2	Eav lx	Uo	Ul
With glass	0.4	5,1	0.38	0.76
Without glass	0.48	5,5	0.39	0.81

$$\frac{\Phi_{without\ glass}}{\Phi_{with\ glass}} = 0.89$$

Fig. 6. Light distribution curves with and without protective glass at different angle of maximum intensity and main photometric indicatrs, that can be achieved



a). б).

Фиг. 6 Mean luminance change– a) and U0 - b) at different angle of maximum intensity at the case without glass (dashed line) and with plane protective glass (solid line)

When there is protective glass, however, exactly the light emitted at great angle to the normal falls on the protective glass at angle, at which the reflection coefficient is big and the absorption coefficient is small. Thus the protective glass acts as a filter exactly at the zones, where greatest effect is expected and actually the luminance on the road decreases and the increase of the angle of maximum intensity above 65^o becomes useless.

The results, obtained are absolutely valid for the light distribution considered in the paper. When another light distribution is taken into account, the results may be different, but the general conclusion is that the inner reflection decreases the positive influence of the wide light distribution.

Conclusions

The use of plane protective glass in the road luminaires is accompanied with an effect of inner reflection, which influence cannot be neglected.

This effect gets stronger with the widening of the light distribution curve of the luminaire.

A great part of the luminous flux, that is redistributed by the optical system at angle $\gamma > 60^0$ to the normal is reflected from the protective glass to the inside of the luminaire and is thus lost.

This effect can be eliminated by using convex protective glass, upon which the light of the luminaire falls nearly normal for all solid angles.

References

[1]. ALUMINIUM-REFLEKTOREN FÜR DIE LANGLEBIGE RUNKTLICHTQUELLE www.alux-luxar.de, LICHT,4 2011
[2]. Farchtchian N,LED-Kaltlichtguelle fur fasezoptische Systeme, LICHT 2010, Wien
[3]. Belloni P, Vazquez- Molini D., Fernandez- Balbuena A., Neuentwicklung von Holichtleiter system mitt verbesseetem Wirkungsgrad, LICHT 2010, Wien
[4]. Jordanow W, Effiziente Entwicklung nichtabbildender Beleuchtungsaptiken mit Hilfe von Raysets
[5]. Richter Ch., Status der LED im Umfeld der energieeffizienten Straβenbeleuchtung. LICHT 2010, Wien
[6]. Жанъ В., Хуа Ш., О рабочих характериках светилъников со светодиодам в КНР, Светотехника, 3, С29-31, 2010.
[7]. Кончи Икеда, Расчет компактного светильника с учетом многократных отражениий между лампой и отражателем, Светотехника, №4, 2009, с. 52-56.
[8]. Шварц П., Экономические и екологические недостатки дорожново освещение светилъниками с плоским защитнъим стеклом. Светотехника, 4, 2009, с28-30