

IRRADIANCE MODEL AND SIMULATION OF A LIGHTING LED SYSTEM

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The current paper is presenting irradiance distributions produced by different power LEDs arrangements on the target surface. A LED assembly irradiance 3D model is developed from individual lambertian light sources to determine the irradiance distribution on an illuminated surface. The total irradiance pattern is significantly different from the lambertian/gaussian distributions notably in cases of heterogeneous lighting assembly.

Keywords: irradiance, LED, distribution/ layout

1. Introduction

Applications in industrial, public, artistic or even domestic lighting are redefining the quality of illumination thanks to technical and economical characteristics of the emerging solid state lighting. The light intensity control, the illuminance pattern design on the floor, and colors combinations are becoming basic features in a modern super efficiency lighting system. The effort to cut lighting maintenance costs is developing smart lighting devices enabling self-checking and remote connectivity [1]. The relentless increasing of the electric power prices and the European Union requirements for eco-friendly technologies are establishing LED devices as the large scale lighting lamps in the forthcoming future.

LED technologies have been highly improved to deliver the lighting market with super-efficient devices. The LED efficiency has been increasing from 0.1lm/W to 276 lm/W, in less than half a century [2]. Fig. 1 shows out the steep rise of LED efficiency while the traditional lighting systems (fire, incandescence or fluorescence devices) have developed almost flat [3]. Today, the efficiency of a pure white LED is limited by the theoretical 300lm/W [4].

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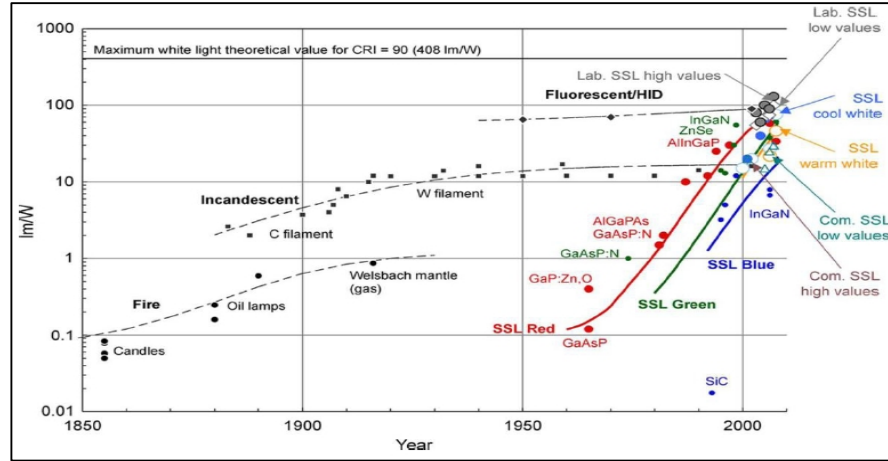


Fig. 1 SSL efficiency evolutions [3]

LED is the best electron – photon converter of all of the lighting devices. Fig.2 shows that the red&blue LEDs exceed a top 20% conversion rate [5].

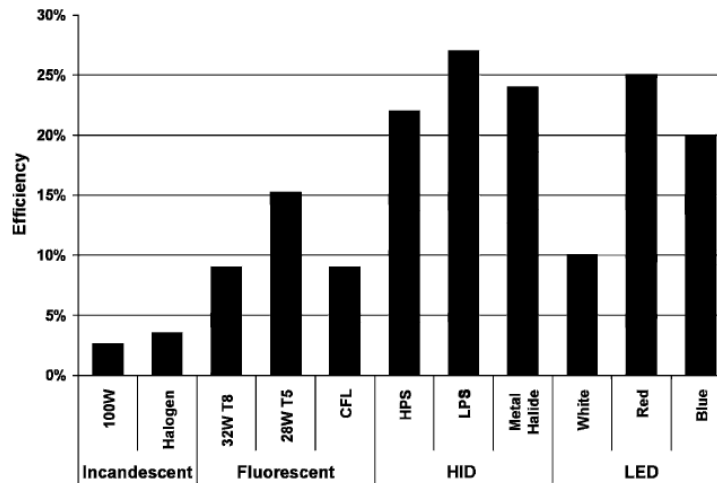


Fig. 2 Conversion efficiency for traditional vs. LED lighting [5]

The Color Rendering Index (CRI), which is a quantitative measure of the colour appearance relying on the correlated colour temperature of the source, is

ranging from the worst 0 (mono-chromaticity) to the best 100 (full chromatics). LED employs 80 points of CRI, close the highest score (Fig. 3) [6].

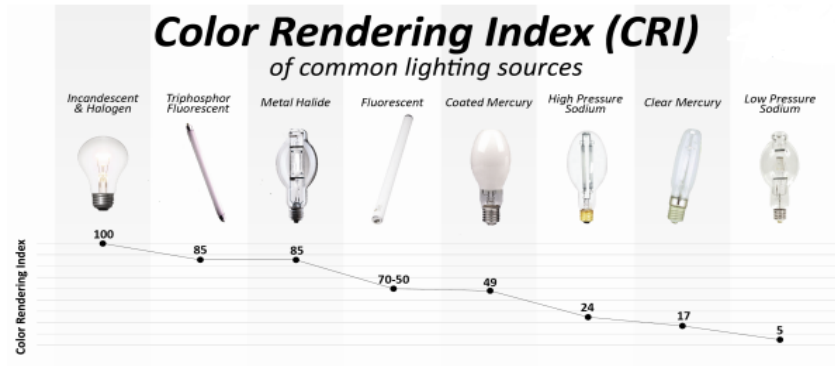


Fig. 3 CRI index for traditional lighting sources [6]

The LED lamp is enabling the color temperature design by using the coordinate chromaticity (Fig. 4), which is a powerful tools to deliver the target screen with the desired spectrum [7].

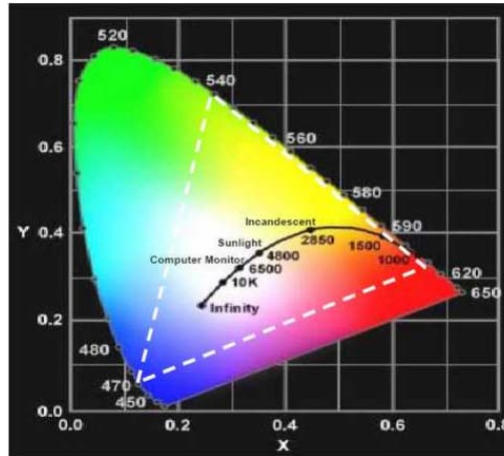


Fig. 4 Chromatic diagram CIE 1931[7]

Other LED major benefits in comparison with the conventional incandescent lamps are:

- A lifetime ranging from 35k to 50k hours. The lifetime strongly depends on the forward current and the thermal management of the device [8]
- The LED packaging technologies are space-efficient.
- Cold light beam. No relevant thermodynamic process occurs during a LED beam trip within the air.
- Easy switching. A power LED enables micro-seconds turn-on and turn-off times with no lifetime damages.
- Lower losses of the transmitted luminous flux pattern [9].
- Dimming features with practical no color changes.
- Vibration and shock proof.

In an ambient with low or even none natural light, random successions of artificial light and shadow is requiring the human's eye a great effort to accommodate the changing lighting conditions. The faster the light is changing the longer the time the eye is taking to adjust its sensibility. Eventually, this accommodation process could make the scene unclear to the eye. A high contrast could lead to a temporary loss of the visual perception, by an excessive stimulation of the eyesight mechanism. Accordingly, in order to comfort the eye and the scene, a LED lighting system is able to perform a certain pattern of the irradiance, in terms of both level and shape.

The present paper is developing an irradiance model provided by a multi-lamp assembly on a target surface. Different LED arrangements have been considered in order to compute the irradiance output onto the target.

The irradiance model is MATLAB simulated. MATLAB is a high-level language and interactive environment [10] fitting the computing requirements of the irradiance model herein.

The present irradiance model is enabling the multi-LED lighting system to deliver the desired irradiance pattern onto the target floor. The model is designed to allow the irradiance pattern with no need for beam forming, which is a lot cost-cutting. With no external lens, the LED lighting system avoids impairments due to optical loss.

2. Radiometric quantities and Models

2.1 Radiometric quantities

The following radiometric quantities are used to define the irradiance model [11], [12]:

- a) Radiance intensity, $I_r(x, y, z)$ is the radiant flux Φ_r divided by the elementary solid angle $d\Omega$, $I_r(x, y, z) = \frac{d\Phi_r(x, y, z)}{d\Omega}$
- b) Irradiance, $E_r(x, y, z)$, is the radiant flux to the elementary receiving area dA , $E_r(x, y, z) = \frac{d\Phi_r(x, y, z)}{dA}$

2.2 Irradiance model

According to the relations above, the elementary radiant flux is given by:

$$I_r d\Omega = E_r dA = d\Phi_r \quad (1)$$

Therefore:

$$E_r = I_r \frac{d\Omega}{dA} \quad (2)$$

The solid angle $d\Omega$ is given by:

$$d\Omega = \frac{dA \cdot \cos \theta}{R^2} \quad (3)$$

θ is the viewing angle between $d\vec{A}$ and the line-of-sight given by $d\vec{\sigma}_n$, R is the radius of a sphere $S(L, R)$. $d\sigma_n$ is the projected surface of the elementary dA on the sphere.

Fig. 5 is showing the solid angle definition. The dA elementary surface, at the distance R from the origin L , is seen under the same angle as the $d\Omega$ surface located at the length of 1 unit from the origin L .

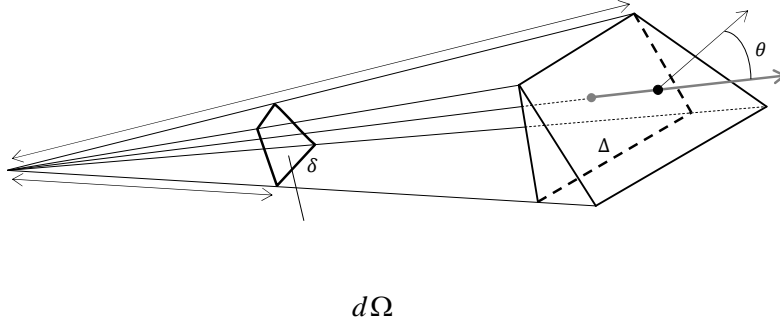


Fig. 5 Solid angle definition

The equations (2) and (3) combine to give the irradiance produced by the source in L on the receiving area:

$$E_r(x, y, z) = I_r \frac{\cos \theta}{R^2} \quad (4)$$

Let us consider n LEDs placed at points $L_k(x_k, y_k, 0)$, $k = \overline{1, n}$, all on the same level $z=0$. Each k^{th} LED intensity $I_{r,k}$ will contribute to the total irradiance E_r of the LED system, at a point $P(x, y, z)$ on the receiving surface:

$$E_r(x, y, z) = \sum_{k=1}^n I_{r,k} \frac{\cos \theta_k}{R_k^2} \quad (5)$$

In order to make the model simple, an intensity Lambert pattern will be considered:

$$I_{r,k} = I_{r,0} \cos(\theta_k), \quad \forall k = \overline{1, n} \quad (6)$$

θ_k is the viewing angle related to the k^{th} line-of-sight:

$$\vec{r}_k \cdot \vec{u}_z = |\vec{r}_k| \cos \theta_k \quad (7)$$

$\vec{r}_k = (x - x_k)\vec{u}_x + (y - y_k)\vec{u}_y + z\vec{u}_z$, where $\vec{u}_x, \vec{u}_y, \vec{u}_z$ are the visors of the Cartesian coordinate system. From $\vec{u}_x \vec{u}_z = \vec{u}_y \vec{u}_z = 0$ and $\vec{u}_z \vec{u}_z = 1$, it results that $\vec{r}_k \vec{u}_z = z$ and:

$$\cos \theta_k = \frac{z}{|\vec{r}_k|} = \frac{z}{\sqrt{(x - x_k)^2 + (y - y_k)^2 + z^2}} \quad (8)$$

Combining (5), (6) and (8), the total irradiance is:

$$E_r(x, y, z) = \sum_{k=1}^n \frac{z^2 I_{r,0}}{\left[(x - x_k)^2 + (y - y_k)^2 + z^2 \right]^2} \quad (9)$$

The equation (8) is the irradiance model of the LED lighting system.

2.3 LED system arrangements

Fig. 6 shows a 5 LED system positioned in the level $z=0$. 4 LED lamps are circling the 5th LED located in the circle center.

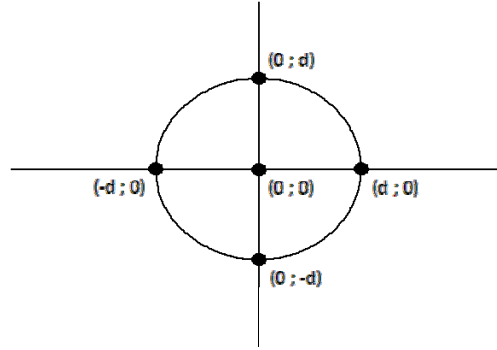


Fig. 6. Circular arrangement of a 5 LED assembly

An alternative lighting arrangements is shown in Fig. 7, where 8 LEDs are placed in a d step grid network.

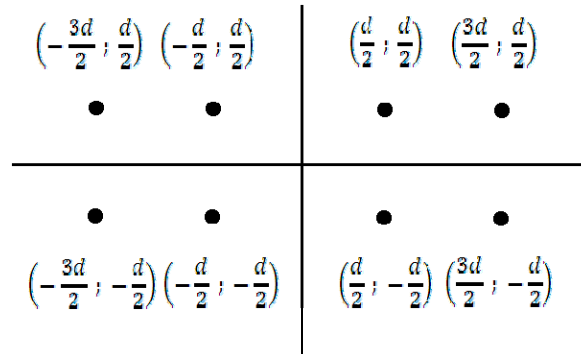


Fig. 7. Grid arrangement with 8 LEDs

3. Results

The 5 LED assemblies produce the irradiance distributions shown in Fig. 8, Fig. 9, and Fig. 10, for three lengths of d and $I_{r,0} = 1000 \text{ W/sr}$.

For $d=0.4\text{m}$, the irradiance distribution is much more homogeneous, due to a high overlapping of the light components. The irradiance distribution resembles a single-lamp dome-shaped pattern, featuring cvasi-lambertian cross-sections. The dome top irradiance is almost five times the centric single LED irradiance at the same level, while the dome is providing uniform lighting to a larger receiving area.

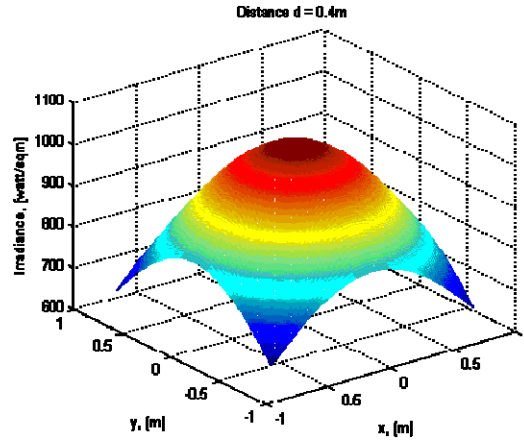


Fig. 8. Irradiance distribution for a circular arrangement with $d=0.4\text{m}$

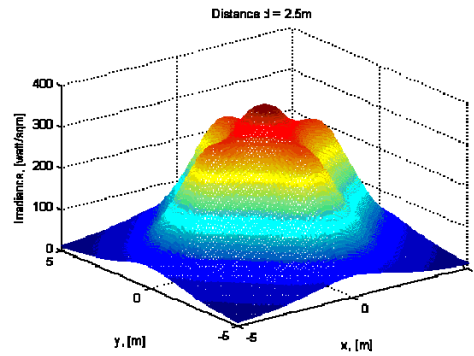


Fig. 9. Irradiance distribution for a circular arrangement with $d = 2.5\text{m}$

For $d=2.5\text{m}$, the distribution in fig.9 shows out a ridge irradiance, mainly provided by the central LED, overlooking foothill irradiance fed by the four neighboring LEDs.

Fig.10 shows out that, for $d = 4\text{m}$, the irradiance distribution is a five tower pattern, a tower a LED. The distance d is long enough to break up the system into parts.

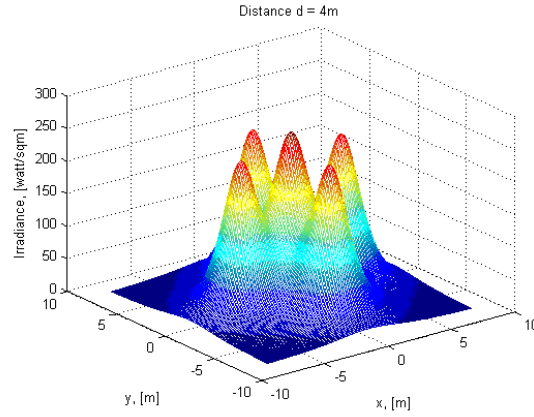


Fig. 10. Irradiance distribution for a circular arrangement with $d=4\text{m}$

Fig. 11, Fig. 12, and Fig. 13 demonstrate the irradiance distributions produced by a grid LED assembly. Three d grid steps are considered, $d = 0.4/2.5/4\text{m}$, $I_{r,0} = 1000\text{ W/sr}$, and $z = 2.15\text{m}$. The longer the distance d , the coarser the irradiance distribution on the receiving area. The eye comfort is given by the shortest $d = 0.4\text{m}$ of the grid steps.

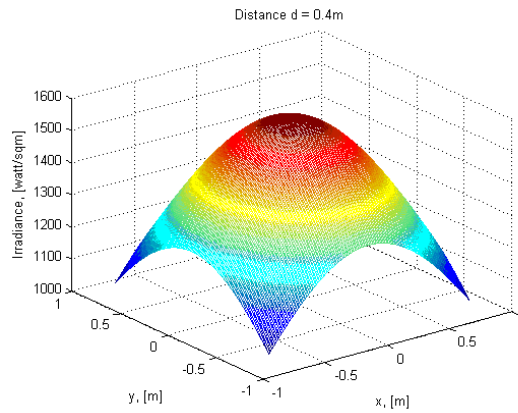


Fig. 11. Irradiance distribution of a LED grid with $d=0.4\text{m}$

Fig. 11 shows out a Lambertian distribution of the irradiance on the target floor if the LEDs are located close to each other, $d=0.4\text{m}$, so as the total irradiance comply the desired pattern.

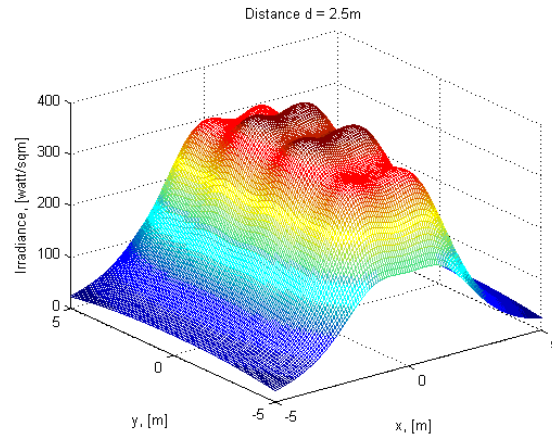


Fig. 12. Irradiance distribution of a LED grid with $d=2.5\text{m}$

An increasing of the grid step length, to $d=2.5\text{m}$, makes the total irradiance getting non-uniform, as shown in Fig. 12. Individual ridges are starting to pop out from the pattern. A further increase of the grid step length, to $d=4\text{m}$, makes LED irradiances distinguishing from each other, as seen in Fig. 13.

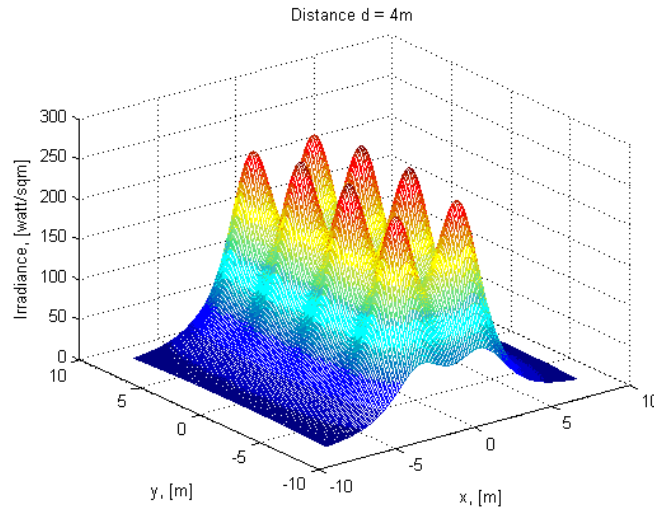


Fig. 13. Irradiance distribution of a LED grid with $d=4\text{m}$

Fig. 14 proves that the irradiance distribution for $d = 4\text{m}$, is non-Lambertian. The lighting system will make the scene a blend of daylight, twilight, and darkness.

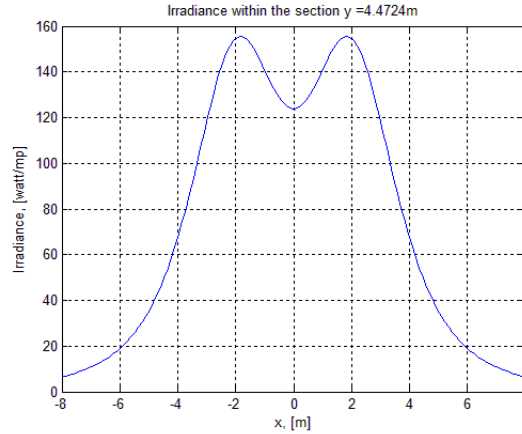


Fig. 14. 2D Irradiance distribution for a 8 LED grid assembly with $d = 4\text{m}$

4. Conclusions

An irradiance model is determined to simulate lighting solutions for different geometrical LED lamps arrangements.

The irradiance pattern uniformity is strongly depending on the LED lamps locations in the emitting surface and the intensity properties of LEDs. Each and every LED in the assembly is delivering a beam of the irradiance model. The beams are blended onto the target floor to result the total irradiance.

There is no general rule to design the LED assembly layout but the requests of the lighting application. However, the lighting comfort of the human eye is claiming for a uniform distribution of the irradiance on the receiving area.

MATLAB tools have been used to simulate the model into lighting solutions. The program is enabling the user to load the number of LED lamps, the LED locations in Cartesian coordinates, the intensity quantities of LEDs. The program is delivering the lighting system irradiance distribution on the receiving surface and cross-sections within the irradiance pattern. Accordingly, an easy assessment of the Lambertian or Gaussian irradiance pattern is allowed.

The program allows the user to compromise the radiant intensities, the number of lamps, and the geometrical arrangements in order to get the required irradiance pattern. The next development of the topics is a more complex irradiance model invoking non-lambertian LEDs.

REFERENCES

- [1]. *Patrick Carner*, Bringing Intelligence to LED Lighting Applications, Texas Instruments, August 2012, <http://www.ti.com/lit/wp/spry211/spry211.pdf> (Accessed on 05.06.2013).
- [2]. CREE News and Events, <http://www.cree.com/news-and-events/cree-news/press-releases/2013/february/276-lpw>, February 2013
- [3]. *Dragomir Radu Bogdan, Prandusa Pantelimon*, Fundamentals of LEDs. Photon generation, electrical mathematic equations and thermal aspects, EPE Iasi, 2012
- [4]. *** Lifetime of White LEDs, U.S. Department of Energy – Energy Efficiency and Renewable Energy, August 2006, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lifetime_white_leds_aug16_r1.pdf (Accessed on 08.06.2013).
- [5]. *C. Michael Bourget*, An Introduction to Light-emitting Diodes, , HORT SCIENCE VOL. 43(7), December 2008.
- [6]. *Rajendra Dangol*, Colour rendering index and colour rendering of LED, Aalto University school of Electrical Engineering, February 2010
- [7]. Sisteme moderne de iluminare bazate pe diode LED, Universitatea Politehnica Bucuresti, Facultatea de Electronica si Telecomunicatii, 2010 http://www.iluminare-led.ro/Sisteme_de_iluminat_cu_leduri.pdf
- [8]. *Yukio Narukawa*, White LEDs with super-high luminous efficacy could satisfy all general lighting needs, *J. Phys. D: Appl. Phys.* 43 (2010) 354002 (6pp); <http://phys.org/news202453100.html> (Accessed on 12.06.2013).
- [9]. *Roberto Faranda, Stefania Guzzetti, Cristian Lazaroiu*, LEDs Lighting: Two case studies, UPB Sci. Bull., Series C, Vol. 73, Iss. 1, 2011
- [10]. <http://www.mathworks.com/products/matlab/>
- [11]. *J. Peatross, M. Ware*, Physics of Light and Optics, Brigham Young University, 2011.
- [12]. *Coroiu Ilioaara*, Studiul intensitatii luminoase si al campului luminous ale unei surse de lumina – Lucrare de laborator, Universitatea Tehnica din Cluj-Napoca.