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MODELING LIGHT PROPAGATION IN A FRESNEL LENS WITH AN ELECTRICALLY CONTROLLED NEMATIC LAYER

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Abstract: This work is dedicated to the modeling of the optical properties of a Fresnel lens with an electrically controlled layer for optoelectronic devices. The modeling was performed using SolidWorks and Zemax software packages. The analysis of the nonuniform distribution of the electric field in the acrylic – nematic liquid crystal system was conducted. A method was developed for creating an optical layer of a complex shape with a variable refractive index.

It is shown that the proposed structure makes it possible to create electrically tunable lenses with a wide range of focal length adjustment via an electric field, using a nematic liquid crystal layer of less than 100 μm. The causes of optical aberrations were identified, along with ways to eliminate them.

Keywords: nematic liquid crystal, Fresnel lens, electrically tunable lens.

1. Introduction

Optical systems with electrically tunable focus offer several important advantages over mechanical ones.

These systems lack moving parts, which increases reliability, reduces wear, and makes them more resistant to vibrations and mechanical damage. They allow for fast focal length adjustment, are compact, lightweight, and operate silently. These advantages make electrically tunable optical systems highly promising for use in cameras, augmented reality glasses, microscopes, telescopes, laser systems, and lighting systems.

The development of such systems requires materials with electrically controllable refractive indices. One of the most promising materials for electrically tunable lenses is nematic liquid crystals. These are anisotropic fluids that combine high sensitivity to external electric fields with significant refractive index anisotropy. The maximum refractive index anisotropy (Δn) of nematic liquid crystals can reach values of about 0.6–0.8 in specially engineered materials.

For example, in [1], the development of nematic liquid crystals based on dinatyl-diacetylene with alkoxyl tails is reported, demonstrating Δn values up to 0.62 at 550 nm. A later study [2] showed that for highly anisotropic nematic liquid crystals based on dinatyl-diacetylene, the extraordinary refractive index (*ne*) can reach as high as 2.1, while the ordinary refractive index (*no*) remains around 1.6. For most commercially available materials, the values are somewhat lower. For standard liquid crystals used in displays (e. g., E7, Merck MLC-6815, BL006), Δn is typically in the range of 0.1–0.3.

However, a major drawback of using nematic liquid crystals in electrically tunable optical systems is the maximum thickness of the material layer, which should not exceed 100 μm to maintain the required optical properties. For instance, in [3], a microlens array structure with a total thickness of 20 μm was proposed.

One solution is to use liquid crystals in combination with Fresnel lenses with low segment height. The modeling of the optical properties of such systems is the focus of this study.

2. Operating principle of an electrically tunable lens

Fig. 1 shows the schematic diagram of a Fresnel lens with a liquid crystal layer. It consists of a rigid lens (2) made of optical acrylic and a liquid crystal layer (4), which are placed between transparent electrodes (1).

The operating principle is as follows:

In the absence of an applied voltage, the refractive index of the liquid crystal layer corresponds to the value $n\perp$. The initial orientation of the liquid crystal layer is set using an alignment polymer layer (3).

When a voltage is applied, the liquid crystal molecules reorient, which leads to an increase in the effective refractive index. As a result, the overall optical properties of the acrylic lens – liquid crystal structure change, leading to a variation in its focal length.

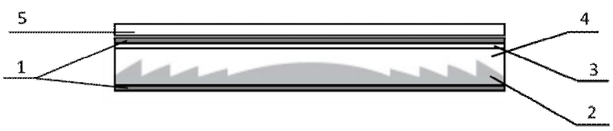

Fig. 1. Structure of a Fresnel lens with an electrically tunable layer: 1 – transparent electrodes; 2 – rigid lens made of optical acrylic; 3 – alignment polymer layer; 4 – nematic liquid crystal layer; 5 – glass substrate.

Let us take a closer look at the processes occurring within the liquid crystal (LC) layer (Fig. 2).

The reorientation process, induced by the application of an electric field to the LC cell, begins in the central region of the LC layer. As the electric field strength increases, the area of homeotropically oriented molecules expands, eventually leading to nearly complete reorientation of the sample – except for a thin surface-adjacent layer.

This reorientation is accompanied by an increase in the effective refractive index of the nematic liquid crystal in the direction of the applied electric field.

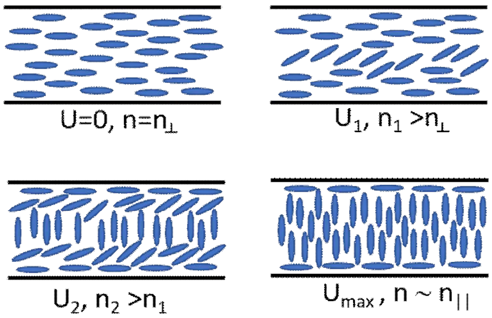

Fig. 2. Reorientation process of the nematic liquid crystal layer under the influence of an external electric field.

Such a device configuration, combined with the properties of nematic liquid crystals, enables the creation of a lens with a wide range of focal length tunability.

3. Input data for the model creation

The serial Fresnel lens FRP125 by THORLABS [4] was selected as the basic element of the model. Its distinctive feature is the uniform width of the Fresnel zones, while the maximum segment depth does not exceed 100 µm, which fully meets the requirements for use in liquid crystal systems. Additionally, the documentation available on the manufacturer's website includes ready-made models of the lens for use in simulation software packages such as SolidWorks and Zemax. The dielectric constant and refractive index of the lens material are 3.2 and 1.49, respectively.

The optical properties of the structure shown in Fig. 1 were simulated using the ZEMAX software package [5]. Fig. 3 presents the profile of the aforementioned lens. As noted earlier, a key feature of this lens is the constant segment width with increasing depth, where the maximum depth does not exceed 100 µm.

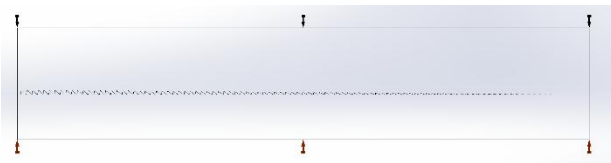

Fig. 3. Profile of the Fresnel lens FRP125 [4].

Figs. 4–6 show the results of ray tracing simulations for the LC–acrylic structure in the following cases: the lens without the liquid crystal layer (Fig. 4), and with the liquid crystal layer having a constant refractive index of 1.3 and 1.6, respectively (Figs. 5 and 6).

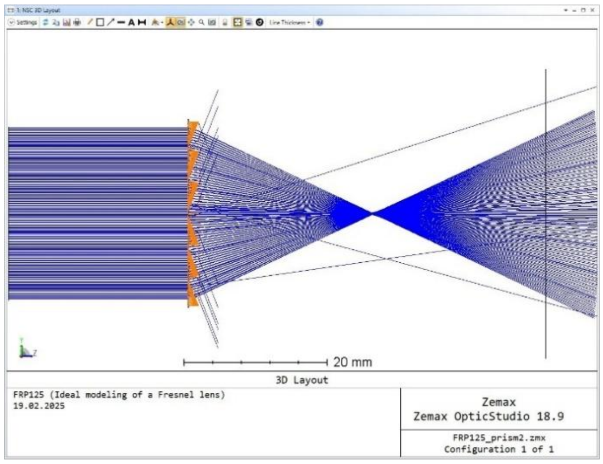

Fig. 4. Ray tracing through the Fresnel lens without the liquid crystal layer.

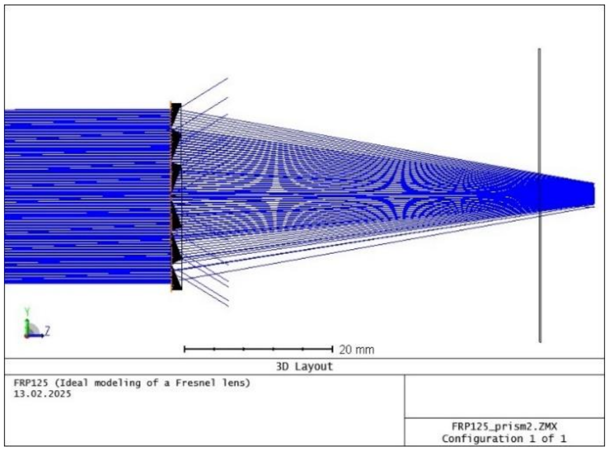

Fig. 5. Ray tracing through the Fresnel lens and liquid crystal layer at n = 1.3.

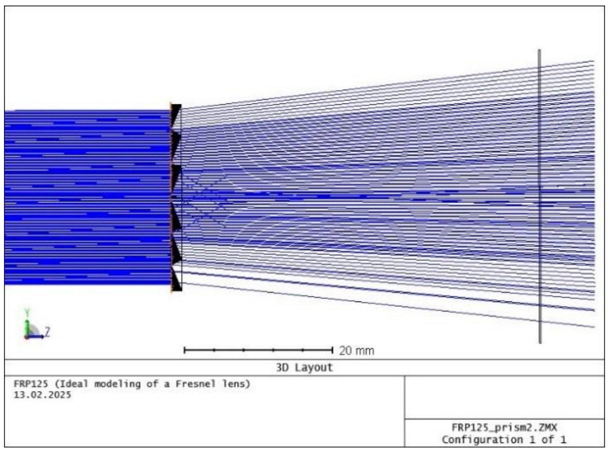

Fig. 6. Ray tracing through the Fresnel lens and liquid crystal layer at n = 1.6.

The models presented above demonstrate a potentially wide range of focal length variation in the proposed system, up to a change in lens type – from converging to diverging. However, the current model does not account for several important aspects of the system. In particular, it does not consider the inhomogeneity of the electric field within the liquid crystal layer, which arises due to the different dielectric constants of the lens material and the liquid crystal. Additionally, the model does not account for the non-uniform orientation of the liquid crystal layer caused by thickness variations and the influence of surface effects.

4. Optimisation of the light propagation model with consideration of dynamic inhomogeneities

To model the electric field distribution in the liquid crystal, the *SolidWorks* software [6] was used in combination with the *EMWorks* add-in [7]. *EMWorks* is a powerful software package for electromagnetic field simulation. It is based on the finite element method (FEM) and enables the analysis of a wide range of electromagnetic problems, including electric field distribution. Figs. 7 and 8 present the results of electric field distribution modeling in the Fresnel lens – liquid crystal layer system.

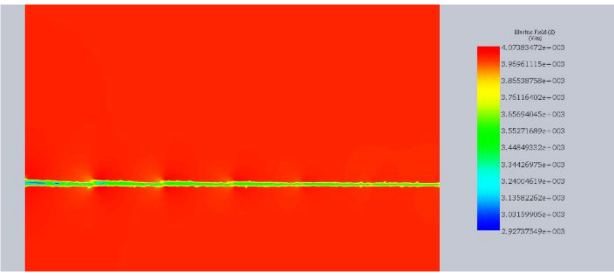

Fig. 7. Simulation results of the electric field distribution in the Fresnel lens – liquid crystal layer system (for the case of homeotropic initial orientation of the liquid crystal layer).

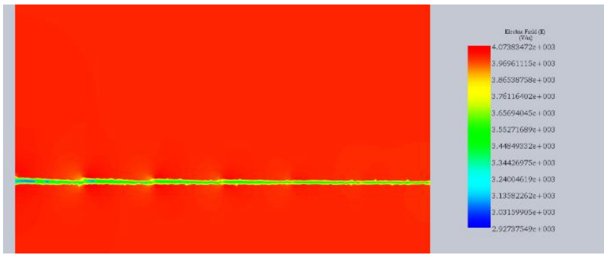

Fig. 8. Simulation results of the electric field distribution in the Fresnel lens – liquid crystal layer system (for the case of planar initial orientation of the liquid crystal layer).

As seen from the distribution provided, the greatest field non-uniformity is observed at the outermost elements of the Fresnel lens, which is caused by the maximum depth of these elements. Let us take a closer look at the outer elements of the lens (Figs. 9–10).

A clear decrease in the electric field intensity is observed with the reduction of the LC layer thickness (the LC location is marked with black triangles). This field distribution pattern, combined with the increasing influence of edge effects in regions with smaller LC layer thickness, leads to a significant impact on the uniformity of the refractive index of the LC layer, especially at low control field values.

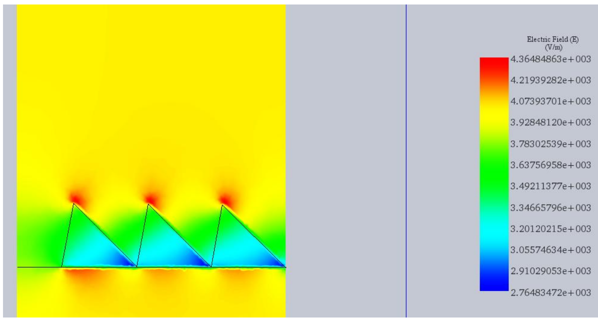

Fig. 9. Simulation results of the electric field intensity distribution in the Fresnel lens – LC layer system for the outermost lens elements in the case of homeotropic initial orientation of the LC layer.

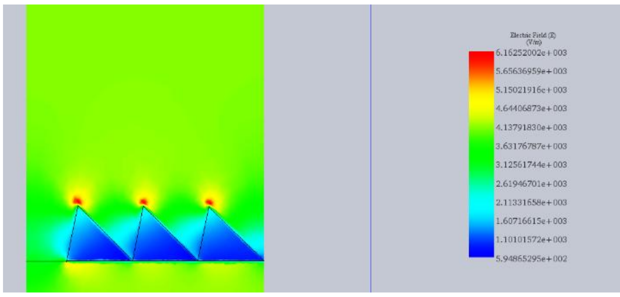

Fig. 10. Simulation results of the electric field intensity distribution in the Fresnel lens – LC layer system for the outermost lens elements in the case of planar initial orientation of the LC layer.

Therefore, to improve the proposed model, we replaced the LC layer with a constant refractive index by a layer with a gradient refractive index. A gradient refractive index means that the refractive index of the material varies depending on its position. This variation may be caused by different factors such as temperature, pressure, or chemical composition. In our case, the external factors influencing this are the effect of the boundary surface and the non-uniform field distribution in the LC layer.

To simulate a material with a gradient refractive index, we developed a custom DLL (Dynamic Link Library) that defines an algorithm for changing the refractive index according to spatial coordinates. Using a custom DLL in Zemax is a powerful way to extend the program's functionality and access more complex material models.

Let us now examine in more detail the proposed algorithm for refractive index variation. At the first stage, we defined a function to describe the variation in the depth of a lens segment while keeping its length constant.

$$S(x)=(1-m(n))\frac{(x \bmod T)}{T}+m(n), \qquad (1)$$

where T is a length of a segment; $n = x/T$ – sequence number of the segment; $m(n)$ – the minimum value of the height of the current segment, which changes linearly from m_0 up to 0:

$$m(n)=m_0\left(1-\frac{n}{N-1}\right),\ 0 \le n < N, \qquad (2)$$

where N is the total number of teeth, a m_0 is the initial minimum value.

Fig. 11 shows a typical view of the function for the case of 10 segments with a monotonous increase in segment depth. As it can be seen from the figure, the function describes the relief of the used Fresnel lens well and can be easily adapted for different lengths, heights and numbers of segments. We also considered the possibility to create a function with an exponential increase in segment depth (Fig. 12), which would allow us to adapt the developed models to a larger number of real optical products.

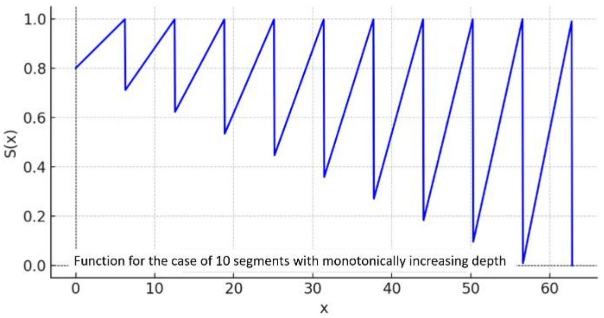

Fig. 11. A typical view of the function for the case of 10 segments with a monotonic increase in segment depth.

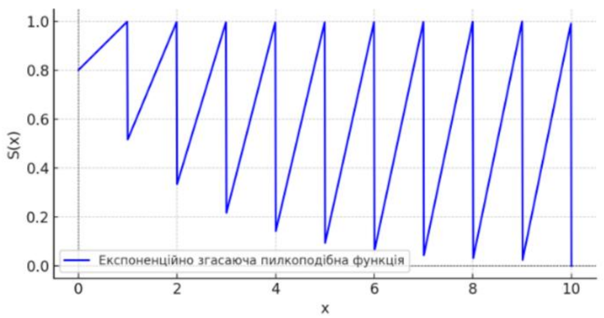

Fig. 12. A typical view of the function for the case of 10 segments with an exponential increase in segment depth.

The next step is to take into account the influence of surface conditions and electric field inhomogeneity.

To do this, the following expression was used:

$$n(S,E)=n_{min}+\Delta n\frac{1}{1+e^{-k(S-S_0)}}\frac{E}{E_{max}}+ \\ +\Delta n\left(1-\frac{E}{E_{max}}\right), \qquad (3)$$

where S_0 is a parameter responsible for shifting the transition centre from the n minimum value to the maximum; k is the is a coefficient that determines the sharpness of the transition (the larger k, the steeper the growth of $n(S)$. The last term guarantees that when $E = E_{max}$ the value of $n(S, E)$ exactly reaches the maximum value of the refractive index $n_{min} + \Delta n$ regardless of the value of S.

A family of refractive index curves for different values of E (with $E_{max} = 10$) depending on the LC layer thickness S is shown in Figs. 13–14. Fig. 13 illustrates the case when the intersection point is located at half the thickness of the LC layer. This type of curve corresponds to a situation with strong anchoring of the near-surface molecular layer and LC layer thicknesses ranging from 2 to 20 μm, which leads to a more abrupt change in the refractive index value.

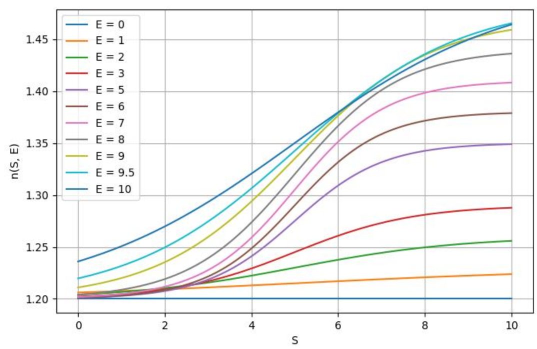

Fig. 13. Family of refractive index curves for different values of E depending on the LC layer thickness, for the case $k = S_{max} / 2$.

Fig. 14 shows a simulated situation where the centre of the transition is shifted towards small thicknesses.

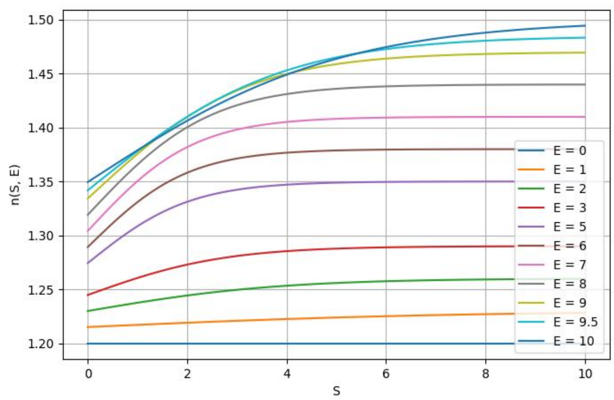

Fig. 14. A family of refractive index curves for different values of E depending on the thickness of the RC layer at $k = S_{max}/100$.

As a result, a less abrupt change in the refractive index is observed, and an increase in the electric field intensity leads to a smoother increase in the refractive index, even in regions with small thicknesses. This type of refractive index distribution is characteristic of cases with weak anchoring between the LC layer and the boundary surface, as well as layer thicknesses of 80–100 μm.

Thus, the use of expressions (1)–(3) for creating a DLL (Dynamic Link Library) makes it possible to simulate an LC layer with a refractive index that varies along the profile of the Fresnel lens. The proposed approach allows for consideration of both the structural features of the lens and the electro-optical properties of the LC materials. Figs. 15–20 show the simulation results using an LC layer with a variable refractive index.

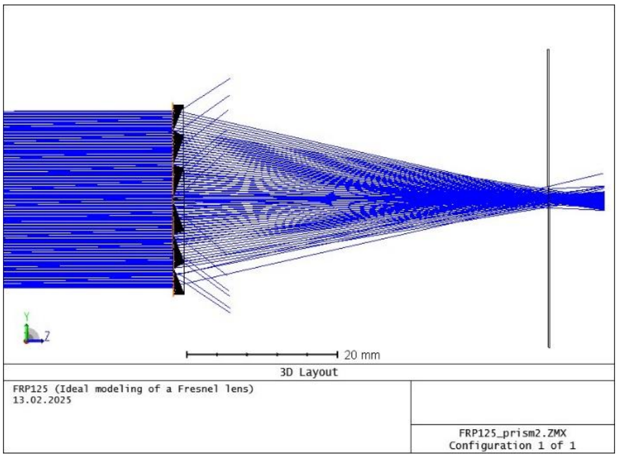

Fig. 15. Ray paths through the Fresnel lens and the LCD layer when the refractive index changes in the range of 1.2–1.3.

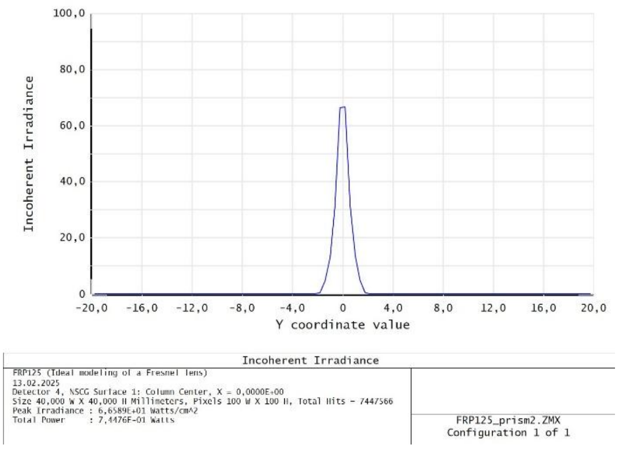

Fig. 16. Distribution of radiation intensity at the focusing point when the refractive index changes in the range of 1.2–1.3.

Analysis of the obtained results showed that a certain blurring is observed at the focal point, caused both by fluctuations in the refractive index of the LC layer and by artifacts resulting from the structural features of the Fresnel lens. However, overall, the focusing properties of the Fresnel lens – LC structure and the range of focal length variation demonstrate strong potential for application in lighting systems, as the proposed approach allows overcoming the limitations associated with the small size of liquid crystal systems.

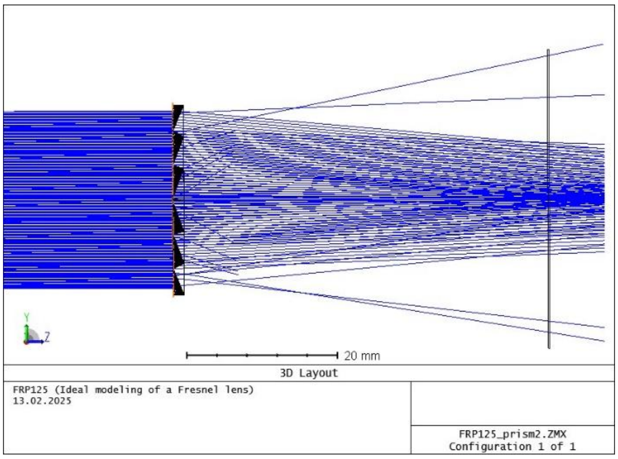

Fig. 16. Distribution of radiation intensity at the focusing point when the refractive index changes in the range of 1.2–1.3.

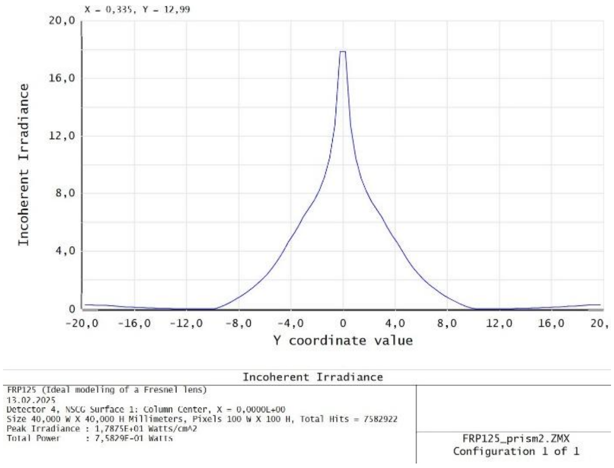

Fig. 18. Distribution of radiation intensity at the focusing point when the refractive index changes in the range of 1.3–1.5.

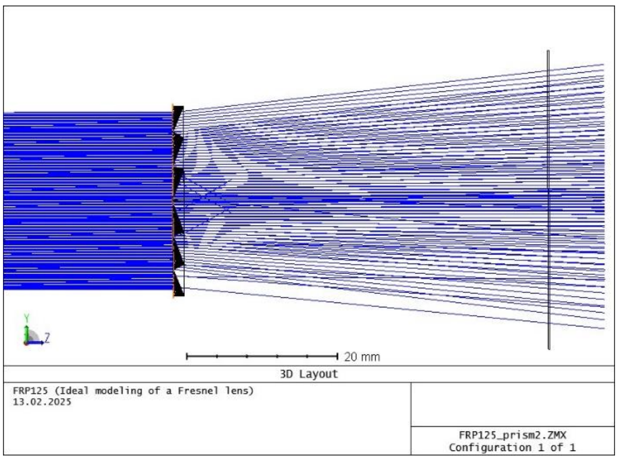

Fig. 19. Ray path through the Fresnel lens and the LCD layer when the refractive index changes in the range of 1.5–1.7.

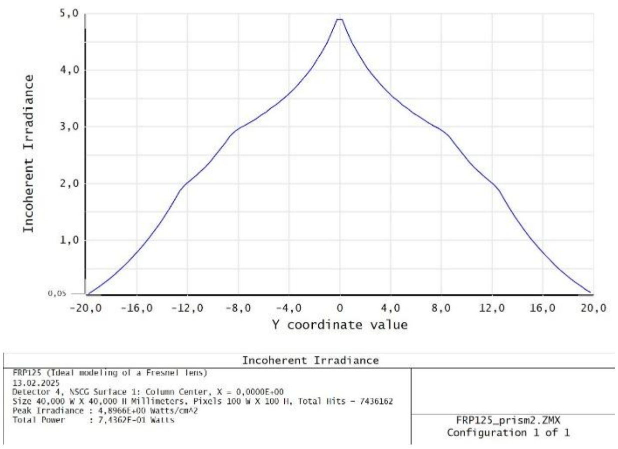

Fig. 20. Distribution of radiation intensity at the focusing point when the refractive index changes in the range of 1.5–1.7.

Conclusions

The obtained results allowed to formulate the following conclusions:

– the electrotunable lens design proposed in this paper enables the creation of large-diameter optical systems, making them suitable for use in lighting applications.

– a method for accounting optical inhomogeneities in the LC layer was developed through the creation of a custom Dynamic Link Library (DLL) for the optical system simulation software ZEMAX. The use of a segment function with monotonic or exponential growth of segment depth allows the proposed models to be adapted to real-world devices. In this work, a real Fresnel lens model FRP125 from THORLABS was used for simulation.

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МОДЕЛЮВАННЯ ПРОХОДЖЕННЯ СВІТЛА В ЛІНЗІ ФРЕНЕЛЯ З ЕЛЕКТРОКЕРОВАНИМ НЕМАТИЧНИМ ШАРОМ

Andriy Fechan, Yuriy Bashtyk

Здійснено моделювання оптичних властивостей лінзи Френеля з електрокерованим шаром для пристроїв оптоеоектроніки за допомогою програмних пакетів SolidWorks та Zemax. Виконано аналіз неоднорідності розподілу електричного поля в системі акрил – нематичний рідкий кристал. Розроблено метод створення оптичного шару складної форми зі змінним значенням показника заломлення. Показано, що запропонована структура дає змогу створити електрокеровані лінзи із фокусною відстанню, яка змінюється електричним полем у широких межах, із застосуванням шару нематичного рідкого кристала < 100 мкм. Виявлено причини утворення оптичних аберацій та способи їх усунення.

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