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ANALYSIS OF ERRORS IN THE RELIEF OF SCATTERING MICROSTRUCTURES IN LIGHT-CONDUCTING SYSTEMS MODELLING

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ABSTRACT

Main technological approaches to production of light-conducting systems with scattering microstructures are considered with a special attention to processing method of the optical material influence on geometrical parameters of the being formed microstructure. Relevance of it is caused by an insufficiency of studying influence of the microstructural scattering element configuration distortion on output luminance distribution of the light-conducting systems (because of the technological features of their production). As exemplified by a light-conducting system made by milling technology, a physically correct simulation of this system is carried out, and influence of the microstructure relief on output luminance distribution is shown. For the simulation, the *Lumicept* program system was used, which has provided physical correctness of the modelling results.

Keywords: light-conducting plate, scattering microstructures, micro-relief errors, illumination LED panels, computer simulation, luminance distribution, design, light-conducting illumination devices

1. INTRODUCTION

At present, about 20 % of all electric energy [1] generated in the world is consumed for illumination, which actualises the problem of power consumption decrease for all illumination devices (ID). In the world, a big attention is paid to design [2–4] and production [5, 6] of energy-effective and ergonomic special IDs with light-conducting systems. In particular, one can name thin LED panels, IDs of LCD display back illumination, IDs plane cabins, car interiors, dashboards and advertising panels among such IDs.

This subject attracts a great interest of such leading global manufacturers as *Asahi Kasei, Denso, Panasonic, Fuji-Film, Toshiba*, etc. So, Japanese company Denso manufactures a wide range of light-conducting IDs for dashboards based on the scattering element technologies [7]. Korean *Samsung* and *LG* based on scattering microelements manufacture optoelectronic devices of mass consumption [8, 9], and Russian companies Kvazar and VOLO develop light-conducting systems with scattering microelements for defence industry. Numerous patents concerning specific character of forming geometry and parametrical functions of scattering microstructural elements distribution, as well as publication in the leading scientific journals and proceedings of international conferences (*Proc. SPIE, Optical Engineering, Applied Optics, Optical Review*, etc.) on the problems of physically correct simulation and design of light-conducting IDs [10–13], give evidence of a great interest for the matter.

Uniformity of radiation distribution between light-conducting devices is provided by micro geometrical elements (light-scattering microstructures) deposited on the light-conducting element surface. Simulation of an optimum microelement structure is rather complex problem requiring considerable computing resources. As a rule, the design results are configuration of the scattering elements, their co-ordinates and orientation on the light-conducting plate surface. One of the main problems of this type ID design is that the design results based on the physically correct laws of light propagation can differ from real lighting characteristics of the manufactured ID. The design errors can be explained by non-availability of the data on the light-conducting system production method and on the technological features of forming the scattering microstructures necessary to construct a correct model used when designing.

In this article, a method of simulating errors of production of scattering microstructures as exemplified by designing back illumination light-conducting IDs of LCD displays is proposed, and methods of forming micro geometrical elements with a description of possible defects of their production are considered.

2. DEPOSITION TECHNOLOGY OF MICRO GEOMETRICAL ELEMENTS ON AN OPTICAL SURFACE

The microelement size is usually tens micrometres, and special technologies are required for their production. Modern technological equipment allows forming microelements for lighting systems with a high precision and acceptable quality. There are several methods of microelements production. The main of them are hot forging, silk-screen printing, engraving and milling.

2.1. Hot Forging

The hot forging is a widespread process of manufacturing products from polymethyl methacrylate (PMMA) and polycarbonate. This method is usually applied to produce geometrical configurations, which size is tens and hundreds micrometres. By means of forging, formation of light-scattering microelements is possible. In this case, the surface thickness and quality high requirements can be applied. The hot forging is performed step by step. A workpiece of PMMA previously heated to the softening temperature (140–190ºC) is installed into the moulding machine, and then a contact is created between the optical surface and the compression mould, giving the workpiece a required configuration [14]. Upon the moulding completion, the finished product is cooled in the compression mould.

When pressing, wavy surface distortions (mechanical waves) can appear, which freeze up when cooling the workpiece [15]. Such distortions have a significant effect on light scattering by microstructures, which influences spatial luminance distribution of the light-conducting illumination devices and can result in a difference from the calculation distribution.

2.2. Silkscreen

The silkscreen printing is one more widespread technology for deposition of microstructures on a plain optical surface. It is also named stencil process.

This technology means light-scattering material deposition. The deposited material layer has thickness of several tens micrometres with a good endurance and durability.

During silkscreen printing, an emulsion layer is deposited on the product surface, and over it a light-scattering composition is applied through a special stencil plate. Using an UV radiation source, the emulsion layer is irradiated, and those sites of this layer where the radiation “fell into” are hardened, and other (unirradiated) sites are washed away. The light-scattering composition is forced through the mesh sites free of emulsion on the product surface when printing. Water and solvent painting compositions, plastisol UV paints and UV varnish can be used as light-scattering materials. The deposited compositions are hardened (polymerised) under UV radiation influence during the printing process.

The stencil plate in this case is usually made using a special mesh of nylon or metallic threads.

Silkscreen printing is considered to be quick and economic technology to manufacture light-conducting systems [16]. However, microstructures formed using it may be non-uniform and not identical, and their configuration may be far from the required [17].

2.3. Engraving and Milling

To perform a laser engraving on PMMA, a CO_2 laser with wavelength of 10.6 μ is used [18]. PMMA has a high absorption factor at this wave-

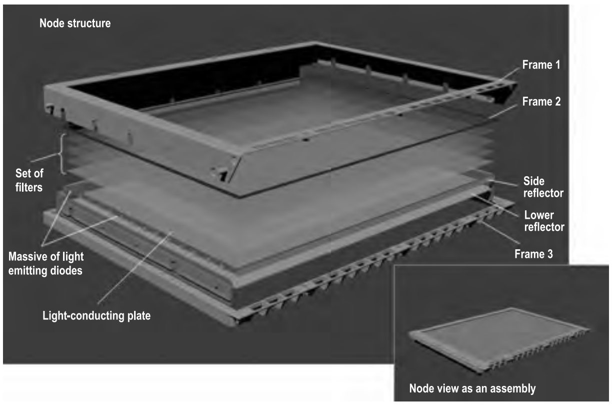

Fig. 1. ID (node) of back illumination of an LCD display

length, which allows (depending on the laser radiation flux) carrying out engraving or cutting the material. When exposing this radiation on a material, its evaporation occurs. Thickness of the evaporated layer depends on the radiation exposure time. Precision technologies used with modern laser machine tools allows moving the laser beam along the set lines with positioning accuracy of up to 25 µm, which makes it possible to obtain micro geometrical elements beginning from 250 µm size. Nevertheless, laser engraving has some disadvantages. In particular, it is impossible to obtain absolutely identical micro-relief over all surface of the material evaporation, and this influences the angular diagram of light scattering [19]. It is also possible to handle non-planar surface by means of a laser but the additional mechanical equipment is necessary to do it.

As for milling, one can produce microstructures of hundreds and thousands micrometre size using it. The milling treatment of a PMMA plain surface is widespread [20]. The milling cutter moves over the working field and cuts off a layer of the light-conducting plate in the locations of microstructure elements. The spent material residues are removed by air from the work-piece surface. The milling treatment can be also applied to produce curvilinear light-conducting systems. For this purpose, upon milling termination, one should give the workpiece a necessary form using a special attachment and then cool it. After these stages are completed, a curvilinear surface with light-scattering microelements is formed. To provide a high precision of microelement forming, high requirements are applied to sharpness of the cutting tool, to removal of the working out products and to cleanness maintenance on the treatment surface.

All above described microstructure manufacturing technologies have its own features, which should be taken into consideration when modelling. On the one hand, it can be residual products of burning when PMMA laser treatment is going on, bad repeatability of the microelement configuration, scratches on the surface due to operation of the milling cutter, etc. On the other hand, an incidentally oriented roughness can be formed (but not a specular surface), or it can be stiffened mechanical waves on the surface around the microelements. All of this significantly influences correctness of the constructed model and, if a maximum approach of the calculation results with work of the real systems is necessary, one should take into consideration all possible distortions. The authors set and solved the problem of correct simulating light-conducting systems with due to account for features of technologies of their production and with coordination of the simulation results with the real product. When solving such problems, some researchers chose a selection of parameters of bidirectional scattering function of element surface of the scattering microstructure [21]. In this article, an alternative approach to the correct simulation is offered.

3. AN EXAMPLE AND RESULTS

Let's consider a coordination of the measurement results of spatial luminance distribution over the light-conducting plate output surface with the

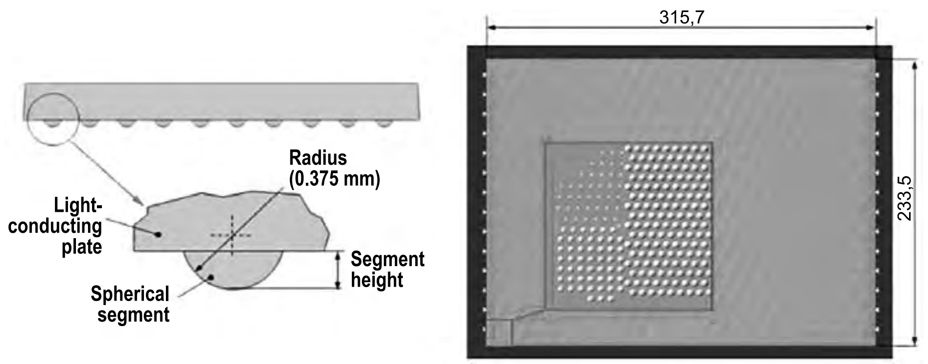

Fig. 2. Light-scattering microstructure

simulation results as exemplified by an ID project (node) of back illumination of an LCD monitor with end face input of the light radiation (Fig. 1).

A model of a light-conducting plate is parallelepiped of transparent PMMA (relative refractive index is the 1.49 and transmission factor is the 0.92) with overall length, width and thickness dimensions of (315.7×233.5×4) mm respectively. Under the light-conducting plate, a diffuse reflector is located (diffuse reflection factor is 0.89). On the plate surface, a microstructure as a massif of more than hundred thousand spherical segments of a constant radius (400 μm) but of an alternating height (Fig. 2) was set. Thirty light emitting diodes were located on both sides of the plate. They radiate in the visible interval and have luminous intensity distribution curve of D type.

The modelling was carried out using the *Lumicept* program system [22]. In comparison with the similar systems “ASAP” [23], “TracePro” [24], “LightTools” [25] and “SPEOS” [26], the *Lumicept* has the most effective algorithm of ray tracing and supports practically all possible from the view point of the beam optics physical effects of radiation propagation and light transformation on optical objects. The *Lumicept* has the most powerful and physically correct model of forming geometrical microstructures and their spatial distribution. Transformation of rays in the microelement geometrical model is also physically correct. All this makes the *Lumicept* an optimum tool for calculation design of complex IDs and of light scattering analysis in optical devices.

In this simulation example, a method of direct stochastic ray tracing was used. The output radiation parameter calculation was carried out using a model of luminance detector located in the plane of the light-conducting plate output edge. The detector model (Fig. 3) consisted of 713 cells (31×23). A cell size was equal to (10×10) mm, and integration cone angle was within ± 2º. The observation direction changed within – 60 to + 60º interval with a pitch of 15º.

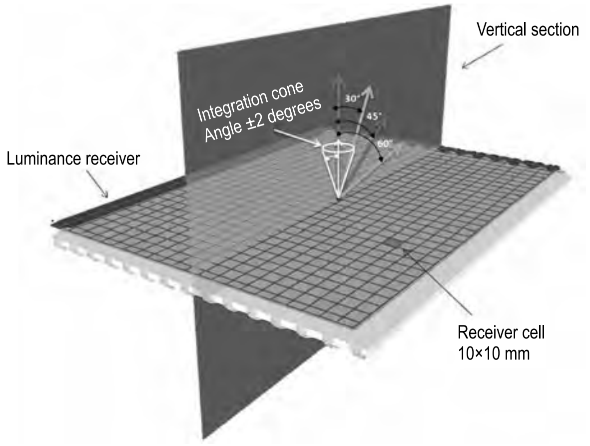

Fig. 3. Conditions of luminance distribution simulation over output surface of a light-conducting plate

During the first attempts of luminance distribution simulation, surface of each element of the scattering microstructure was set being completely smooth, i.e. without any micro-relief on it. The simulation results are presented in Fig. 4, where rise of the luminance level is well seen in the middle area of the light-conducting plate.

At the same time, the measured luminance distribution of the manufactured experimental specimen of the light-conducting plate with a scattering microstructure (Fig. 5) shows a noticeable luminance decrease in the middle area of the plate output edge, which significantly differs from the simulation results presented in Fig. 4. Such a measurement and simulation results discrepancy required to carry out an analysis to clarify its reasons.

As a result of the microscopic analysis of a separate microelement surface (Fig. 6, *a*) parallel grooves (Fig. 6, *b*) were found on it, which obviously arose when working the mould using a cutting tool. These grooves have a pronounced regularly directed structure, and this can quite lead to changes of angular distribution of light coming out of the

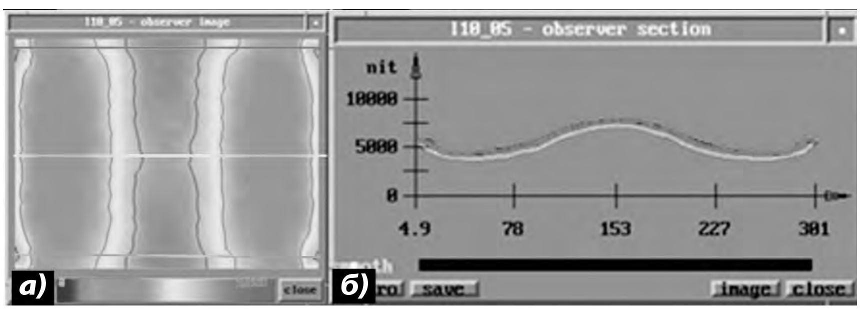

Fig. 4. Results of luminance distribution simulation over a light-conducting plate surface in the event of a completely smooth surface of micro-geometry elements: *a* – spatial distribution; *b* – distribution in the marked sections

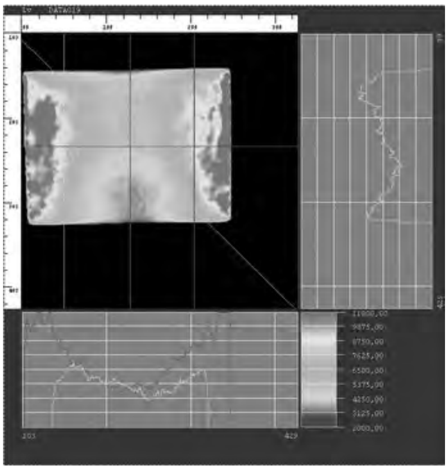

Fig. 5. A result of measuring luminance distribution over a manufactured specimen light-conducting plate output edge

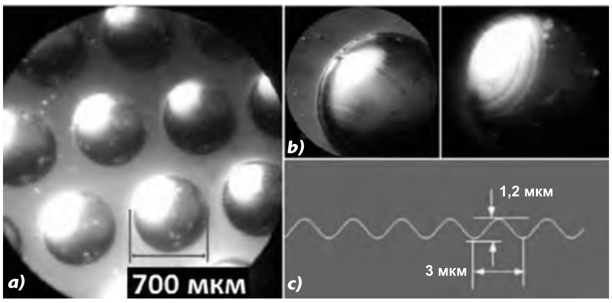

Fig. 6. Pictures of scattering elements microstructures (a) and of grooves on a microelement surface (b). Parameters of the groove relief (c)

plate and, thereby, have a significant effect on spatial luminance distribution. Unfortunately, exact measurements of either bidirectional scattering function [27], or of fine-grain relief on the spherical segment being a separate microgeometry element, not yet possible. Therefore, an attempt of reproduction of averaged parameters of the micro-relief observed in a microscope was made.

At the following simulation stage, a micro-relief consisted of sinusoidal grooves of 1.2 µm depth with the period of 3 µm (Fig. 6, *c*) was set on the surface of each element of microgeometry, which optical properties did not differ from the properties of the light-conducting plate.

In the first simulation experiment, micro-relief groove were placed in parallel to the longest side of the light-conducting plate, which corresponds to zero angle of the relief deviation. As it can be seen from Fig. 7(1), at different observation angles, luminance and its distribution on the plate edges is changing. During the second simulation experiment, direction of the micro-relief grooves was set with a deviation of 15º for all microstructural ele-

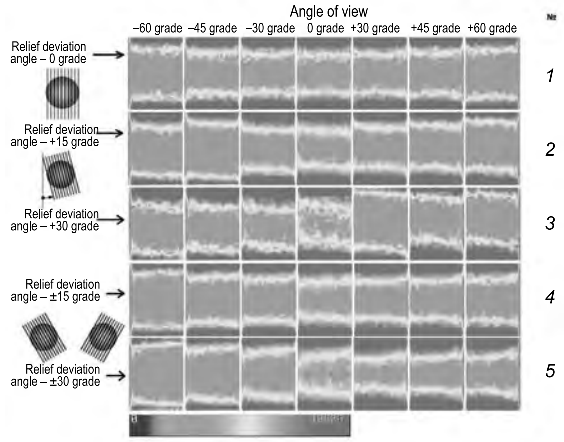

Fig. 7. Results of simulating output luminance distribution over the surface of a light-conducting plate taking into account micro-relief

ments. Respectively, it is seen from Fig. 7(2) that luminance distribution on the edges is asymmetric, and this is noticeable for observation angles of – 60,– 45, + 45 and + 60º. In the third simulation experiment, the relief for all microelements was turned by 30º. The correspondent luminance distribution (Fig. 7 (3)) strongly depends on the observation angle, and asymmetry is revealed stronger than in the previous experiment. This allows us to conclude that when changing micro-relief orientation, luminance distribution of the radiating light-conducting plate changes its symmetry for different observation angles. During the fourth simulation experiment, nature of micro-relief multidirectional orientation influence was verified. Each half part of the microelement massif is deviating off on + 15° and – 15° respectively. The obtained luminance distributions presented in Fig. 7 (4) save distribution symmetry. However, with increase of observation angle to – 60º, luminance on the light-conducting plate edges decreases.

The fifth simulation experiment differed from the fourth by the relief deviation angle (± 30°) only. In this case, with big observation angles (– 60º,– 45º), luminance decreases. When turning the micro-relief by ± 30°, at the observation angle equal to 0º, the simulation result repeats the measurement results of the light-conducting plate luminance distribution, wherein difference of luminance average values is equal to13 %.

Modelling experiment showed that an “addition” of a microstructural element micro-relief model allows coordinating calculation and measurement results among themselves. In that case, spatial-and-angular luminance distribution depends on the micro-relief orientation.

4. CONCLUSION

Defects of light-conducting system optical surface, arising during manufacturing of microstructure diffusers, has a significant effect on the output light distribution, energy efficiency and ergonomics of an ID as a whole.

Therefore, to obtain correct results of light-conducting system simulation, it is necessary to know and take into consideration the features of microstructural scattering element formation technology.

As exemplified by simulation of an LCD display light-conducting plate with scattering microstructures performed using hot forging, it was found out that relief of microstructural elements influences the general luminance distribution. In spite of the fact that parameters of micro-relief arising on the surface of scattering microstructure elements almost cannot be exactly measured, several simulation experiments allow rather exactly selecting the micro-relief parameters for a further optimisation of this ID. Assuming that the technological process is stable, the obtained parameters of the micro-relief can be used for simulation and design of illumination systems, which light-scattering microelements are manufactured by a similar technology. The authors successfully solved the problem of a correct simulation of light-conducting systems taking into account the features of its production technology, and they developed an approach to simulation of output luminance distribution and to coordination of the results with the real luminance distribution. Use of the described method will help to improve quality of light-conducting system design in the future.

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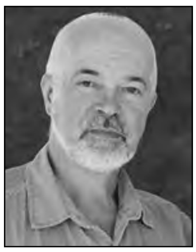

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