Paper

Application of Diffraction-based Optical Components in Advanced Lighting Systems

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Abstract

In this paper novel approaches to optical beam shaping for lighting systems are presented. Application of various computer generated micro/nano-structured optical components is discussed. In contrast to conventional diffusers manufactured using grinding, sandblasting or etching techniques, the Nanoptiqs components can manage the light in a more complex way, they can create sharp edges, generate complex shapes of light distribution curves and maximalise efficiency of optical systems. Simultaneously, relief micro-structure of the elements is convenient for effective mass-replication and can be easily transferred to wide variety of substrates. Unique properties of Nanoptiqs components allow for new designs and light distributions which are presented in a form of newly developed lighting fixtures.

Second part of this paper discusses optical elements with volume modulation of refractive index and their application in lighting systems. The nature of volume modulation can not only further increase efficiency of the products, but it also significantly improves resistance of the elements to environmental conditions. The volume micro-structure contained inside the material is also very resistant to scratches and other mechanical damages. Design and manufacturing of volume optical elements is discussed with regard to management of polychromatic light. A crucial factor for wider application of volume elements is mass-replication. A novel approach to effective mass-manufacturing is presented based on vacuum deposition technique with a surface precursor layer. Optical function of the volume element is demonstrated on a real lighting system.

Introduction

The invention of LED sources into the lighting industry initiated new requirements on optical components used for beam management [1]. Besides the application of refractive and reflective elements, some luminaire manufacturers started to use optical components based on diffraction of light in their products [2]. The simplest example of such an element is a diffuser based on random micro-structure which scatters the light and softens the light distribution. Such elements are used either separately or in combination with other conventional optical components (typically lenses or reflectors). In addition to well-known conventional optical diffusers (usually manufactured using grinding or etching techniques) also synthetic diffusers were developed based on point-by-point calculation and direct writing of the micro-structure. As a consequence of this approach various asymmetric light distributions can be created which are difficult to achieve with conventional diffusers [3]. However, the direct approach to the design and manufacturing of micro-structures (or even nano-structures) can result in much more sophisticated optical elements (or even whole optical systems) which can hardly be called diffusers. Although these components can look very similar to conventional diffusers (from a macroscopic point of view), in optical function they are much closer to optical elements. They can also work in imaging regime as conventional lenses or even as holographic imaging systems. This contribution analyzes various approaches to the design and manufacturing of generalized diffusers and new complex micro- and nano-optical components. Besides the relief-type modulation a volume modulation of optical properties can be used for manipulation of light on a basis of diffraction. Volume elements can further improve general properties of the products and their resistance against various environmental influences. Applicability of volume structures in lighting applications have been analyzed in detail also with regard to mass-production processes. Volume gratings (or general volume diffractive elements) are usually recorded inside a plan-parallel layer and thus they are well protected against most environmental conditions. Moreover, in some cases, the diffraction efficiency of volume structures can be significantly higher than the efficiency of relief-type elements. This paper analyzes the application of volume elements for managing white light beams from LED sources. Dispersion of light, angular and spectral selectivity and other effects are discussed. Volume diffractive elements have also significantly different requirements on mastering and mass-replication technology. Innovative approaches to manufacturing of volume structures will be presented including optical recording processes and mechanical replication techniques. IQ Structures developed a general approach to design and manufacturing of optical systems for lighting applications which applies mentioned elements in complex systems. Combination of conventional components with optical micro- and nano-structures gives us an ability to achieve interesting light distributions together with new visual design of luminaires. Simultaneous use of volume and relief elements ensures high performance and robustness of the optical systems integrated under the trade name Nanoptiqs.

In the first part of this contribution a general idea of application of diffraction-based optical elements in lighting solutions is presented. The difference between diffusers and more sophisticated optical elements is discussed in detail. General design and manufacturing approaches are briefly summarized and several sample systems are presented. The second part of the paper is devoted to volume optical elements which have a potential to further improve optical properties of micro/nano-structured optics. Key principles are explained and analyzed. A novel approach to mass-production of optical micro/nano-structures with volume modulation of refractive index is presented together with realized real optical systems for lighting applications.

Diffraction based optical elements

The optical systems for managing light in lighting applications were always mostly based on simple refractive and reflective elements with smooth continuous surfaces. For design and modeling of such systems, ray-tracing approaches were heavily used because of their simplicity, effectiveness, and also a relatively high accuracy. However, a good correspondence between theory and performance of real systems was conditioned with continuous shapes and absence of any micro- or nano-features. Statistical properties of light were not included in calculations, as reflection and refraction were not strongly dependent on a level of coherence. Thus the ray-tracing approaches could give precise predictions. However, already from the beginning, there was one group of components which do not contain smooth surfaces at all and which often consisted from tiny features at a micrometer level or even smaller. Such elements, called diffusers, were used to homogenize light output, increase divergence of beams, mixing colors, etc. Technically, refraction and reflection principles cannot be used to describe functionality of such structures, because they are based on diffraction and scattering of light from a tiny features. However, if the function is fairly simple and coherence of light is poor, their description can be based on simplified bidirectional scattering distribution function or similar approaches. The diffusers are commonly manufactured using various grinding, sandblasting or etching processes. Since then many components with similar visual appearance, matt, diffuse surfaces with blurring effect have been called diffusers. It is often automatically assumed that an element with such visual appearance must behave as a diffuser, cannot generate sharp cut-offs in light distribution and must suffer from unwanted scattering of light causing energy losses. A couple of decades ago when optical holography was used for the first time in light management and redistribution applications, such elements started to be called holographic diffusers. Although they can visually resemble classical diffusers, their function can be very far from those conventional ones. And most recent diffraction-based elements which are calculated in computer point-by-point with a sub-micrometer resolution and manufactured using ultra-high precision writing techniques should not be called diffusers at all, although their evolution maybe started from something inspired by classical diffusers. From a point of view of manufacturing the difference is as big as the difference between a statistically random distribution and precisely calculated shape. From optical point of view, the diffraction-based micro/nano-optical elements can work with a particular level of coherence of light and utilize constructive and destructive interference effects to achieve precise light distributions. Due to low coherence of polychromatic light such effects cannot play a dominant role on large smooth continuous surfaces, but they can be of high importance when the feature size reaches a level of few microns. And thus, even if such structures can look visually similar to conventional diffusers, their function is much more complex. They can work as real optical elements with imaging properties or create general wavefronts exactly as holograms. They can create sharp edges, desired inhomogeneous spatial light distributions, divide light into multiple beams, mix colors in a precise way and many others.

Diffraction of white light usually suffers from strong dispersion which causes unwanted coloring effects. Random diffusers can suppress such coloring as they naturally blur light in all directions. However, such blurring is in contradiction with achieving sharp light distributions without significant losses of energy. Once the micro-structure is more smooth (and organized), the dispersion can be significant. One of the possible approaches to avoiding unwanted coloring due to dispersion is operating the optical micro/nano-structures in higher diffraction orders (see figure 1).

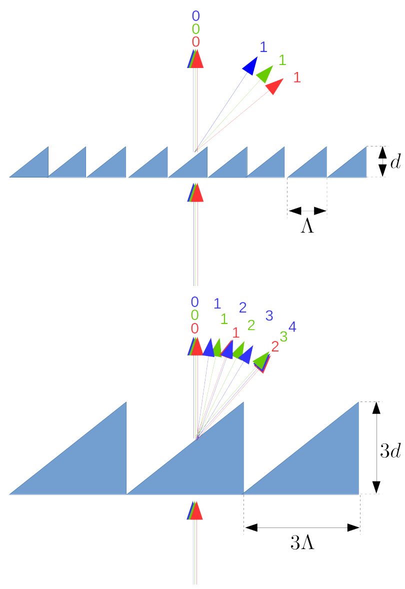

Figure 1: Principle of achromatic function based on higher order operations. For 1-st order grating (top) the dispersion is strong, dominant orders for different wavelengths propagate in different directions. In case of 3-rd order design (bottom), each wavelength diffracts in different order, but all dominant orders have the same direction of propagation.

The micro/nano-optical elements from Nanoptiqs family can be based on various types of micro/nano-features. In figures 2 and 3 there are examples of two different micro/nano-structures designed for particular applications. The element from figure 2 is based on micro-dots filled with various blazed gratings. In this case, the output light distribution is very complex and forms a general image when illuminated with white light. The element from figure 3 is based on rotationally symmetric features organized in a hexagonal grid. The light output is also rotationally symmetric with a precisely defined shape. It is important to emphasize, that both elements from figures 2 and 3 have practically the same visual appearance which is very close to the appearance of a conventional random diffuser. However, their internal structure and optical function is totally different.

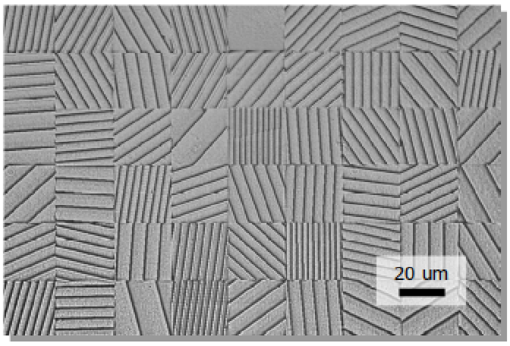

Figure 2: Example of micro-structure of one type of Nanoptiqs element based on blazed micro-dots. A macroscopic visual appearance of such an element is very close to a conventional random diffuser, but the optical function is completely different - particularly, the displayed micro-structure generates a very complex image.

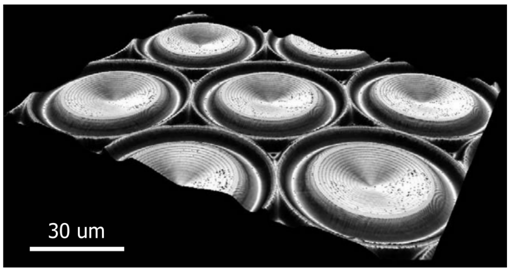

Figure 3: Another type of Nanoptiqs micro-structure. Rotationally symmetric features generate a precise rotationally symmetric light output.

In figure 4 there are examples of manufactured lighting fixtures based on Nanoptiqs solution using a combination of multiple optical elements. An application of such innovative optical systems allows for new visual designs, extremely low-profile bodies and precisely defined light distributions.

Figure 4: Examples of low-profile luminaires with a homogenized luminance over the output aperture and a directional light distribution characteristics based on Nanoptiqs solution.

Volume optical elements

From a point of view of diffractive optics, one of the most important characteristics of an optical element is whether it exhibits a volume behavior or not. The word "volume" here represents the fact that light diffracted in particular direction is created through an interference of contributions from different places within the volume of an optical element. As a consequence of this property the light output can be strongly dependent on an angle of incidence (which is more likely a disadvantage) and the diffraction efficiency can be much higher than in a case of thin elements, often close to 100% (which is a potential advantage). Although the relief structures can exhibit volume behavior (and they often do when the aspect ratio is close to 1 or higher), it is much more interesting to consider structures with volume modulation of optical parameters - i.e. plan-parallel layers with smooth interfaces (without any relief), where a whole optical function comes from inside of the layer. For the lighting industry such components are extremely interesting not only because of a potentially higher diffraction efficiency, but also because of an inherent protection of the active part of the micro-structure. The key issue in application of the diffractive optics with volume modulation of optical parameters is an effectiveness of mass production of such structures.

Design and simulation of volume diffractive elements

In contrast to thin diffractive elements modeling of interaction of light with a volume structure is much more complicated. Because of strong coupling effects inside the material it is practically impossible to derive a simple analytical model of interaction. Strong resonance effects can appear which lead to a high sensitivity of optical function to the polarization of light, the angle of incidence, and the wavelength. Simplified theories such as the Kogelnik's theory of coupled waves [4] are applicable only in special cases, typically for a weak harmonic modulation of material parameters, a limited number of diffraction orders and/or a small or none deviation from the Bragg condition. On the other hand, an absolute efficiency of a selected diffraction order is more likely a question of the thickness and the geometry of reconstruction than the shape of modulation function and, in many cases, it can exceed 90% or even closely approach 100%. The main question is if such a volume element can effectively operate in polychromatic light.

A detailed answer to the question of functionality of volume elements in polychromatic light is far beyond the scope of this contribution and thus we will limit the analysis to an extension of the approach presented in previous sections for relief elements. As it was shown, an operation in higher orders can result in achromatic behavior when particular wavelengths can effectively diffract in different orders which propagates all in the same direction. To achieve a higher order operation, it was necessary to increase depth of modulation - depth of relief in case of relief elements - accompanied with an increase of period of the micro-structure. An equivalent step in the case of elements with volume modulation of refractive index is to achieve an over-modulation of the refractive index or to increase the thickness of the layer (or both). In the first step this principle was tested in simulations based on the RCWA technique ([5], Rigorous Coupled Wave Analysis). For simplicity the diffraction efficiency of the zeroth diffraction order was evaluated for a spectrum of visible wavelengths and a varying angle of incidence. Results of simulations are summarized in figure 5.

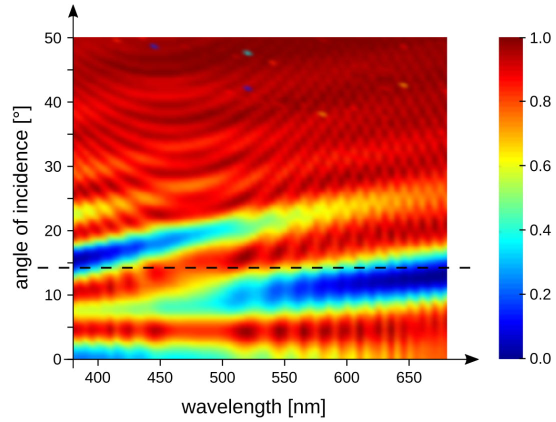

Figure 5: Dependency of efficiency of the zeroth diffraction order of an over-modulated grating with volume modulation of refractive index on the wavelength and the angle of incidence. Blue notches indicate creation of intensive higher diffraction orders. Multiple notches for one angle of incidence and multiple wavelengths indicate achromatic function of the element.

In the graph (figure 5), the red color corresponds to high efficiency of the zeroth order close to 100% when other diffraction orders are negligible. If any other diffraction order rises significantly, the efficiency of the zeroth order must rapidly decrease. Such an effect will create notches in the efficiency diagram (blue areas in figure 5). As it is seen for some geometries (values of the angle of incidence) there are multiple notches corresponding to different wavelengths. Thus if the structure is illuminated with polychromatic light under a particular angle of incidence, it can show achromatic behavior - high efficiency for multiple wavelengths. It can be shown from analysis of higher diffraction orders that various wavelengths diffract with high efficiency to different diffraction orders, but all in the same absolute direction - white light is bended without a visible coloring effect. However, although the simulations confirm predicted function, it can be difficult to achieve an over-modulation in real volume elements. Key factor here can be a choice of material and approach to creating modulation inside the volume of the material.

The diffractive optical structures with volume modulation of refractive index are widely used in image holography, where the most important property, coming from the volume nature of holograms, is wavelength selectivity of reflection volume structures. As a consequence, the holograms can be observed in light of polychromatic sources without significant blurring caused by the dispersion effects. Such holograms are manufactured using a direct optical interference recording process. Main issues with a mass replication is a low speed of the copying and high requirements on the recording material (which result in low availability and high prices of such materials). Another issue can also appear connected with low resistance of final material to environmental effects and thus a reduced long-term stability of the products. For application in lighting and similar fields an alternative approach to mass production must be invented.

To verify experimentally the above discussed theoretical principles, an over-modulated grating was created in a photo-polymer recording material using an interference recording process. An operation of volume structure in a higher order (particularly the 3-rd order) is demonstrated in figure 6.

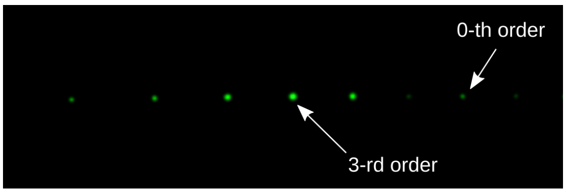

Figure 6: **Diffraction pattern from an over-modulated volume grating in a photo-polymer material operating in the 3-rd order.**

In many cases it is not possible to create a sufficient modulation inside the material using a simple interference field of two or more waves. A novel approach was developed in IQ Structures based on a contact copying of special masks produced using direct laser [6] or electron beam [7] writing techniques. In such a case very general volume micro/nano-structures can be created inside the recording material. In figure 7 there is an example of volume elements manufactured using the contact copying process with a special mask (generated in computer and written using the direct-write lithography).

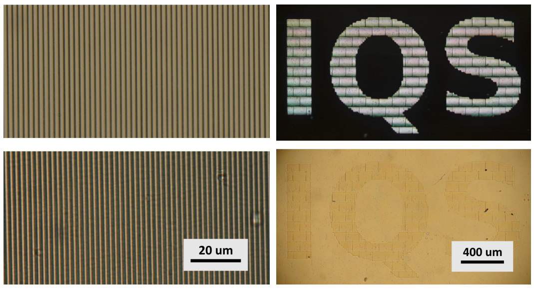

Figure 7: **Examples of the volume elements in photo-polymer materials. The top left image displays a magnified mask used in the contact copying process, the bottom left image is a micro-structure of the created volume element. The top right image shows a more general volume element illuminated from the backside with white light with oblique incidence. The white image observed from the front demonstrates an achromatic function of the element. The bottom right image displays the same element illuminated from the backside with diffuse light.**

Effective manufacturing of diffractive elements with volume modulation

To avoid the delicate recording process which requires a sufficient sensitivity of a volume material to the light, the structure can be grown (e.g. built layer-by-layer) using another techniques such as a thin layer vacuum deposition and similar. The main question is how to achieve a micro/nano-structuring of the material during the layer-deposition processes. The presented approach, developed by IQ Structures (patent pending), is based on a vacuum deposition of a dielectric material on micro/nano-structured surfaces. In this process, a micro/nano-structured surface serves as a precursor for creating the final structure. The precursor itself is a thin relief element which can be mass-manufactured in conventional processes used in holography or other fields. In the second step a layer of additional material is deposited on the surface. Because of the precursor properties, the deposited layer is not homogeneous, but has some shape induced by the precursor relief. To achieve such behavior, a micro/nano-structure of the precursor must be specially designed. A relation between the precursor parameters and the distribution of deposited material is not straightforward and must be precisely calculated prior to the manufacturing of precursor structure.

In figure 8, there is a schematic drawing of the deposition process. In the top and middle rows, an additional material is deposited on a precursor surface with different parameters of the deposition process and, in the end, the structure is covered with a protective layer. Such layer can be typically applied in a lamination process. In the first case the deposited material is separated for particular features on the surface of precursor and it does not create a compact layer. In second case the deposited layer is compact. The bottom row in figure 8 displays a similar process with an additional surface polishing prior to the lamination.

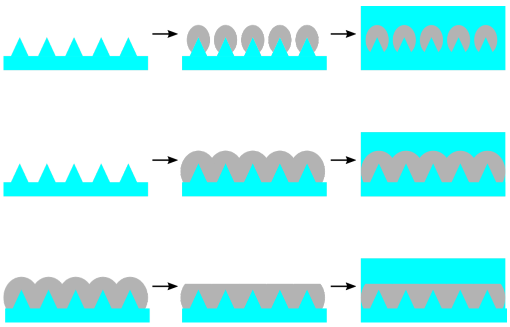

Figure 8: Schematic drawing of the deposition principle. The top row demonstrates a deposition of the material on a precursor surface and subsequent covering of the surface with a protective layer. The middle row represents another case with different parameters of the deposition process, when the deposited layer is compact. The bottom row depicts an additional step of surface polishing prior to the application of a cover layer.

Figure 8 only demonstrates a simple single-step deposition process. Obviously, such steps can be repeatedly applied to achieve much more complex geometries of the volume structure.

The described process was tested and optimized using various combinations of substrates, precursor micro/nano-structures and deposited materials. Typically, materials with refractive index close to 2 or even higher were selected which can create with a poly-carbonate matrix (typical substrate material with refractive index $\sim$ 1.6) sufficient contrast to achieve appropriate phase modulation of the transmitting optical waves. In figure 9 there is an SEM image of the precursor (top image) displayed together with an image of the surface after the deposition of high refractive index layer.

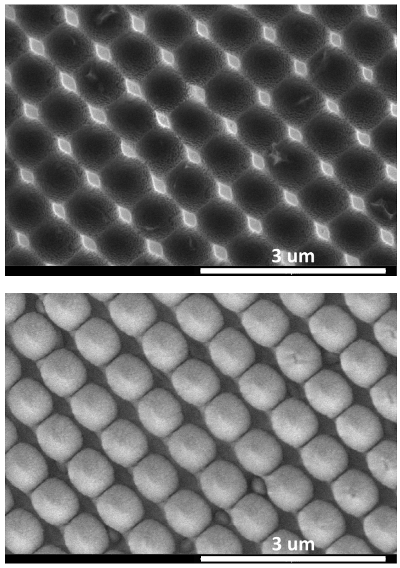

Figure 9: SEM images of the precursor surface used to create a real volume micro-structure (top) and the surface after deposition. In this particular case the deposited layer is not compact and creates separated features. After application of a cover layer these features will represent discrete islands with high refractive index inside the volume of the layer.

As it is seen, the deposited layer is not compact and corresponds to the case from the top row in figure 8. If the parameters of deposition process are changed, the deposited layer can become compact (see middle row in figure 8). This is demonstrated on real sample in figure 10.

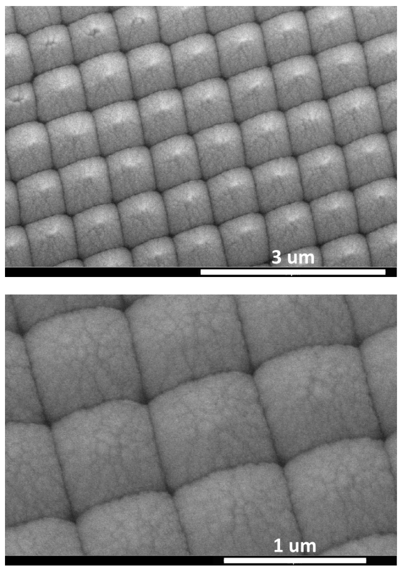

Figure 10: SEM images of a surface after the deposition process with different parameters (with respect to the sample from figure 9). The deposited layer is now compact.

In real applications the micro/nano-structure is usually not completely periodic as in the above presented examples. The most common is a quasi-periodic pattern consisting of small areas filled with a precisely periodic pattern which changes over the surface of the element. Such a heterogeneous micro-structure is displayed in figure 11. The top image displays the surface of precursor before a deposition of the high refractive index material, the bottom image is another area after the deposition.

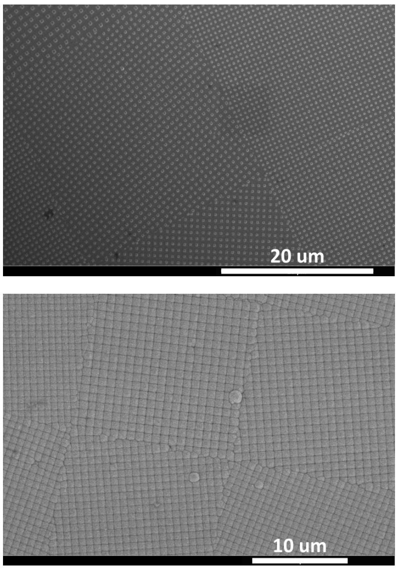

Figure 11: SEM images of surfaces of the precursor (top) and the deposited layer (bottom) in case of a heterogeneous micro-structure, which consists of rectangular areas with dimensions $\sim 20 \times 20 \mu$m filled with different patterns.

A geometry of micro/nano-features after the deposition is also dependent on the material used (besides the parameters of the process itself). In figure 12 there is a comparison of two different materials deposited on the same type of precursor surface.

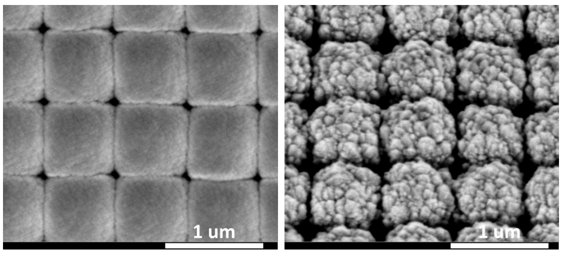

Figure 12: SEM images of surfaces deposited with different materials. The precursor surface was identical in both cases.

Examples of volume elements for lighting applications

Based on the approaches described in previous sections the volume elements were designed for application in lighting systems. There is a simple system displayed in figure 13, which consists only of a single LED and a single planar volume optical element placed in front of the LED chip. Such an optical system produces a rotationally symmetric light distribution with angular width 25° (see bottom image in figure 13). The transmission optical element is a plan-parallel poly-carbonate sheet with smooth surfaces from both sides and a volume structure inside the layer (see top right image in figure 13).

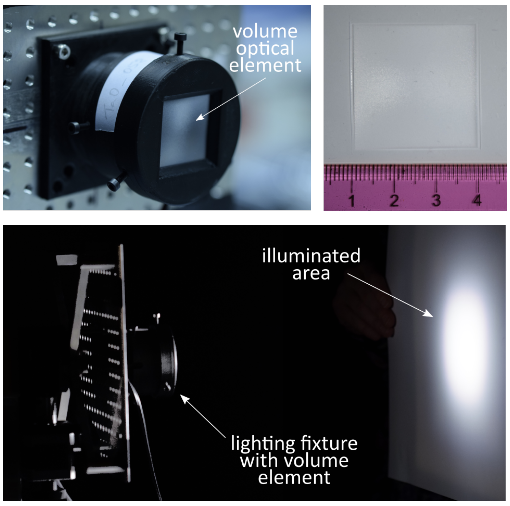

Figure 13: A sample system for application in lighting with a volume optical element. The optical system (top left) consists of only a single LED and a planar volume element (top right). The output light distribution is rotationally symmetric with angular width 25°.

Conclusions

In this paper, novel optical elements for lighting systems were discussed based on optical micro/nano-structures. Various types of micro-features were presented with diffuse-like macroscopic visual appearance, but completely new optical performance. Special attention was paid to micro/nano-structured elements with volume modulation of optical parameters. Optical function of such components was demonstrated on real samples. In all cases, effective mass-manufacturing processes were considered, which play an important role in real-world applications of Nanoptiqs systems. Better performance of optical systems, highly improved robustness and resistance of components and very effective mass-production technology make the diffraction-based optical elements a primary choice for future developments in the industry.

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Organisation

IQ Structures

We use state of the art technology and interdisciplinary expertise to form micro- and nanostructures of materials and their surfaces to enhance products with new functions and properties.

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