Review Article

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Micro-optics in lighting applications

Abstract: The intention of this article is to give a concise overview on current applications of micro-optical components in lighting, including general lighting, automotive lighting, projection, and display backlighting. Regarding the light sources, the focus of this paper is on inorganic light-emitting diodes (LEDs) and the characteristic problems encountered with them. Lasers, laser diodes, and organic light-emitting diodes (OLEDs) are out of scope of this paper. Micro-optical components for current applications of inorganic LEDs may be categorized essentially into three classes: First, components for light shaping, i.e., adjusting the intensity distribution to a desired target; second, components for light homogenization with respect to space and color, and third, large-area micro-optical elements. These large-area elements comprise micro-optical slabs and sheets for guiding, reflection, and refraction of light and are designed without regard to particular details of type, design, arrangement, and layout of the individual light emitters. References are given to textbooks and review articles to guide the interested reader to further and more detailed studies on the problems discussed here.

Keywords: illumination; LED; lighting; light-emitting diode; micro-optics.

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1 Introduction

Lighting is a wide and interesting application field of optics with a significant number of everyday applications including general lighting, automotive lighting, projection, industry, and many more. As the light-emitting diode (LED) has reached a flux level sufficient for lighting applications and as white-emitting LEDs have been invented, the field has experienced a tremendous development. Several central problems of nonimaging optics, such as shaping of the intensity distribution of a lighting system, have been existing with traditional light sources and lamps (such as incandescent, halogen, fluorescent, gas discharge), too, but the advent of the LED has changed the conditions or brought new optical challenges, for example, light mixing with respect to intensity and color distribution.

Micro-optics, on the other hand, is another multifaceted subfield of optics, too [1–3]. Originally driven by telecommunication applications, its technological basis has traditionally been semiconductor microfabrication processes. Over the years, polymers and liquids as constituent materials or for fabrication processes came into the focus of interest and gave rise to new research directions such as optofluidics. Nevertheless, precision manufacture of miniaturized optical components or with small dimensions in its function-relevant parts still represents the core of micro-optics on an industrial level.

The purpose of this article is to give a brief overview of micro-optical solutions for technical problems encountered in lighting applications a clear focus to the LED as the light source. The field of LED lighting is moving fast; for many typical lighting applications, LED standard solutions are not as completely established as in traditional lighting. Thus, there is still room for new developments. The article restricts itself to applications of visible light and to applications with nonvanishing market relevance, and does not strive for completeness and too much technical detail.

Modern LEDs represent complex optoelectronic components available in very different package designs for different target applications, and the package generally comprises one ore more LED chips, phosphor platelets or phosphor casts for luminescence conversion, bond wires, electrostatic discharge (ESD) protection diodes, and a primary lens. Luminous efficiency, i.e., the fraction of the emitted luminous flux and the consumed electric power, is a key figure of merit for LED lighting, and care should

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be taken to clearly distinguish the level on which these quantities hold, for example: on chip level, packaged LED level, or luminaire level, and including or without the electronic control gear (ECG).

This article treats the packaged LED as a given optoelectronic component. Although even chip design, luminescence conversion, and package design imply interesting micro-optical problems, such as roughening and scattering to improve light extraction, I will not discuss them in this article, as they are discussed in detail in standard textbooks, for example [4, 5], and review articles [6]. Rather, I will describe micro-optical elements in the light path between the primary light source and the exit surface of the lighting system in this article.

A key quantity encountered in this context is étendue. Étendue ξ ultimately is a four-dimensional volume in phase space and describes the spatial and angular geometric 'extent' of a light beam transmitted by an optical system.

The étendue of an optical system is obtained from integration of its differential $d\xi$ over both area and solid angle area element over the entrance pupil of the system. The differential $d\xi$ is given by

$$d\xi = n^2 dA \cos\theta \ d\Omega, \tag{1}$$

where dA is the area element, $d\Omega$ is the solid angle element, n is the refractive index of the source space of the rays, and θ is the polar angle.

The reason for the importance of this quantity is that a conservation law holds for it as the light propagates through a lossless optical system. Lossless means optical systems without absorption, gain, scattering, diffraction, and Fresnel or total internal reflection 'losses'. Thus, reducing $d\Omega$ (i.e., emission to a narrower cone) by an optical system is only possible if dA increases and vice versa.

Moreover, the étendue of an optical system limits its capability of transporting flux. It can be shown that the luminous flux Φ transmitted by an optical system is given by

$$\Phi = \frac{1}{n^2} L\xi \tag{2}$$

if the light source is a spatially uniform Lambertian emitter with a luminance of L. Equation (2), thus, describes a special case, but this case is an excellent approximation in many LED-related problems.

One should distinguish between étendue of an optical system and the étendue of a light source, as described by equation (3) in the next section. For a more detailed discussion, see [7] and [8].

2 Micro-optics for light shaping

Package design has a major influence on emission characteristics and on optical efficiency of a LED, and a variety of packages exists in current LEDs for both surface and volume emitter chips. The most prominent package types are premold and quad flat no-leads (QFN), ceramic, and chip-on-board (CoB). Both premold and QFN LEDs are assembled in plastic cavities ('premold') molded on a metal leadframe. Depending on the application, the plastic material is white and reflective when the application requires a high luminous flux or black and absorbing when the application requires a clear optical separation between the individual chips. A ceramic substrate is preferred for high-power chips to improve heat transfer. CoB packages are typically applied for multichip arrangements in a dense array.

Regarding primary optics component, these package types either exhibit a clear window, or a luminescence converting cast, or a molded clear lens. The requirements of the target application determine the optical design of the package. For example, applications requiring collimation of the emitted light, such as automotive headlights and (more generally) projection systems, are limited by the étendue of the light source. The source étendue ξ of a light source with a light-emitting area A, a FWHM emission angle 2σ, and embedded in a medium with refractive index n is given by [7]

$$\xi = \pi n^2 A \ \sin\sigma \tag{3}$$

The minimum étendue of a LED-based system is, thus, determined by the light-emitting surface of the chip and its FWHM emission angle. Embedding the chip in a material with a refractive index higher than unity, increases étendue. Thus, for étendue-critical applications (such as projection), one prefers packages in which the chips directly emit to air, and primary lenses assembled with an air gap over the chip. In other applications, with general lighting on first position, total emitted luminous flux and luminous efficiency in terms of emitted lumens per consumed electrical watt is a more important criterion. Here, embedding the chip in a transparent optical medium other than air helps to extract photons out of the chip due to the smaller difference in the refractive indices of the semiconductor chip and its ambient. Embedding of the light source is accomplished by either a polymer cast or a molded lens consisting of epoxy- or silicone-based polymers, typically.

Owing to the compact dimensions of a typical package and given the typical dimensions of current LED chips, the chip cannot be considered as a point source but rather has to be treated as an extended light source for the lens. Thus, the optical design of the lenses is found by software-based design optimization routines, and the result is typically an aspherical lens described by polynomials.

From a theoretical point of view, a construction given by Weierstrass [9] has found renewed interest as it gives a design rule for a spherical primary lens that couples to air all light that has been generated from the chip and coupled to the surrounding lens medium. The size of a lens, however, exceeds that of typical current LED packages by a factor of 2–5. As a general rule-of-thumb, bigger lenses exhibit a higher optical efficiency. This becomes clear upon comparing a big and a small lens over a chip of the same size: With the bigger lens, the chip covers a smaller fraction of the total lens footprint. The chip surface in any LED package represents a major source of losses due to re-absorption of light that has been reflected back from the lens. Thus, for all surfaces in the footprint of the primary lens, highly reflective materials are desired to improve photon recycling. Photon recycling means that a photon that has undergone a first reflection at the lens surface gets a second chance to escape the lens upon a second reflection at the lens footprint.

The purpose of subsequent secondary optics is then to shape the emission characteristics of a light source, i.e., to provide the desired intensity distribution of the system from a given intensity distribution of the source. For traditional light sources including incandescent, halogen, and fluorescent lamps, secondary optical components typically consist of macroscopic lenses (standard or Fresnel type) and mirrors (smooth or faceted) or mirror grids.

While many traditional light sources exhibit an omnidirectional intensity distribution, the vast majority of commercial LEDs has a Lambertian intensity distribution with a full-width half-maximum (FWHM) emission angle of 120°. Many applications, in contrast, require a smaller FWHM angles, for example, 24° and 36° cones for spot lights, or even more sophisticated intensity distributions, as encountered in street lighting or office lighting. Thus, a number of companies have specialized themselves in design and fabrication of secondary lenses for LED applications. A wide product portfolio for many typical applications and for LEDs from all major manufacturers is available. It includes optical components based on refraction, total internal reflection, and reflection, and considers single LEDs as well as linear array arrangements of LEDs. The étendue of the light source together with the desired target FWHM determines the required minimum dimension of the optical component.

In some applications, the design of a secondary lens has not only to fulfill the technical task of providing a particular intensity distribution, but has to match industrial design criteria and a distinguished appearance of the product, too. A marked example in this context is the flash lens in mobile phone cameras for a single LED or a pair of LEDs. Flash lenses often exhibit a Fresnel design to reduce the thickness of the lens (compared to a continuous lens profile with the same functionality) and to hide the colored appearance of the luminescence conversion phosphor. Mounting the Fresnel lens behind a window, or mounting it with its flat side pointing outside, prevents dust deposits in the teeth of the lens structure and provides a smooth outside surface. Such LED flash lenses are primary examples of precision-molded plastic optical components. Regardless of the design complexity and manufacturing precision, they have to meet demanding price targets to be competitive in the consumer market.

Tunable, variable, and adaptive optical devices have been a strong subfield of micro-optics during the last years. In lighting applications, in contrast, this trend has not entered with the same vigor yet. Notable exceptions are a study of an area luminaire with adjustable intensity distribution [10], in which light-shaping lenses and corresponding coupling features of an edge-coupling-based area luminaire are actuated with respect to each other, and recent developments of elastic silicone lenses to reduce space and complexity of an adaptive automotive frontlighting system [11].

3 Micro-optics for homogenization

Shaping of the intensity distribution is not only a technical problem on the scale of a single LED package but also applies to arrays and larger assemblies, too. This becomes clear upon considering the typical luminous flux levels LEDs and luminaires: a mid-power LED emits 10–20 lm, a high-power LED 100 lm, an A-lamp ('light bulb') 250–1100 lm, and an office luminaire 3000–4000 lm. Thus, typical lamps and luminaires require a count from approximately 10 up to a few 100 LEDs arranged in an array.

Regarding A-lamp LED retrofits, products often exhibit white LEDs arranged in a ring-shaped array to match the symmetry of the lamp. A special optical element inside the lamp serves for transferring the Lambertian intensity distribution of the LEDs into a more or less omnidirectional one. Luminance maxima and steep gradients in the intensity distribution may be reduced by scattering the emitted light at a frosted surface of the lamp bulb.

For spot lights, powerful chip-on-board (CoB) LEDs with Lambertian emission characteristics have become available during the last years. They comprise a dense array of chips, sometimes with a phosphor cast covering all chips, such that the light-emitting surface exhibits a diameter of 10 mm and more. To collimate the light from these CoB LEDs, faceted reflectors are preferred. The facets reduce an undesired spotty appearance of the projected light spot. In optical design of these reflectors, not only étendue has to be taken into account but also skewness [7].

White light from LEDs may be generated not only by generation and luminescence conversion on blue light but also by mixing the light from red-, green- and blue-emitting LEDs. Here, these colors can be either generated by direct emission or by luminescence conversion. In such systems consisting of several LEDs emitting at different colors, the problem of color mixing and spatial color homogenization is encountered because multiple or color shadows are undesired in most applications.

A traditional solution for color mixing is the mixing rod, also called lightpipe. Here, the light of all color components is fed into a light guide; while propagating there, it undergoes multiple reflections leading to a homogenization in both intensity and color (see [12, 13] and the references herein). A clearly micro-optical solution to the homogenization problem is the so-called Köhler or fly's eye integrator consisting of two individual or a single double-sided microlens array [14, 15] as a component in a setup of parallelized Köhler illumination units. This approach of using lens arrays for light homogenization has been first described in a patent describing an illumination unit for motion picture projectors [16]. Light homogenization may be regarded as particular problem of beam shaping, in general, and, thus, profits from developments made in different context, for example, laser beam shaping, years ago. For a review article on arrayed optical elements for beam shaping with both coherent and incoherent light, see [17].

Figure 1 shows a schematic of the fly's eye setup. A first microlens array (oriented toward the light source) splits the incoming light into many ray bundles that are overlapped later in the setup. This first microlens array focuses an entering parallel beam into a second microlens array. The divergent ray bundles leaving the second microlens array overlap and, thus, mix the light with respect to space and color. Designs of this setup comprise both systems with two single-sided microlens arrays and systems with a single double-sided microlens array.

It should be noted that proper homogenization action requires incidence angles not exceeding a certain limit. Thus, it is well suited for applications with a small numerical aperture, such as projection systems [18], but not for light sources radiating to a wide angle spectrum. To overcome this problem, a sophisticated variant of the Köhler integrator called shell mixer has been conceived in which the double-sided microlens array is defined on a dome-shaped surface to homogenize light from LED chips [19].

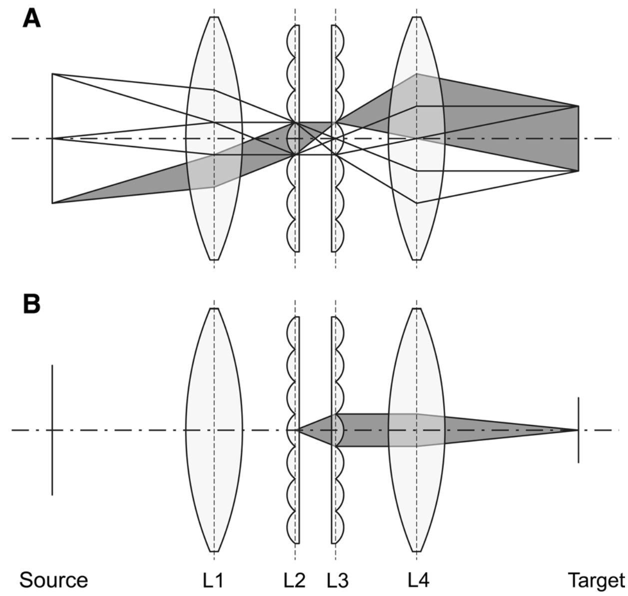

Figure 1 Setup and principle of a fly's eye or Köhler integrator. Divergent ray bundles from the source are collimated by lens L1. A first microlens array, L2, then focuses the entering parallel bundle to a second microlens array, L3, located at a distance equal to the focal length of L2. L3, thus, represents a field lens. Finally, the diverging ray bundle from L3 is directed to the target plane by a lens L4. In practical applications, the microlens arrays L2 and L3 may be combined to a tandem array exhibiting microlenses on both sides of a substrate. Subfigure (A) shows the paths of rays from different positions on the extended source. Any point of the source plane illuminates the full area of the target plane. Thus, the light in the target plane is mixed with respect to space and color, even with an inhomogeneous source. Moreover, the apertures of the microlenses of L2 are imaged by this setup into the target plane, as illustrated in subfigure (B).

Light homogenization is a frequently encountered technical problem in many technical lighting applications, and many nonimaging optical systems benefit from the availability of micro-optical homogenization elements. This holds not only for general lighting but also for illumination in mask aligners as used for photolithography [20], as well as for novel approaches in projection [21] based on parallelization of the imaging channels.

4 Large-area micro-optics

A third class of micro-optical components for lighting applications, and perhaps the most relevant one from an economic point of view, is large-area micro-optics. Large-area optical elements come into consideration as soon as the size, number or arrangement of the light sources, or certain design criteria (such as total thickness) do no longer allow to employ individual light-shaping optics for each source. Large-area micro-optical elements are designed to and intended for performing an optical function irrespective of the position and arrangement of the light source(s) in the system, and a number of such large-area optical elements exist.

In the context of general lighting, certain criteria for illuminance on a target surface and regarding glare have to be met, and these criteria and norms (for example, DIN EN 12464-1, describing illumination of interior workspace) differ among countries and regions. To meet the limits given there and for light shaping, in general, a number of standard large-area glare-reduction slabs consisting of micro-cone or micro-cylinder-lens arrays are available in the market. These slabs are typically fabricated by injection molding or hot embossing processes in optical plastics such as poly(methyl-methacrylate) (PMMA) or polycarbonate (PC), and the typical size of the micro-optical features is in the range of several 100 microns to a millimeter. Designs tailored to the system details and its application may be conceived and fabricated, too, but require significantly higher effort and cost. In the case of linear features (cylinder lenses or prisms), crossed arrangements of the features on a single slab or on two stacked slabs does allow glare reduction and light shaping in two sections of the emission space. The principle of operation of these slabs is refraction. A micro-cone structure, for example, reduces the intensity at high angles by refracting rays entering under high angles toward the surface normal. As luminous efficiency is a major issue, in general, lighting, surface coatings are available for these optical slabs to reduce reflection. Glare-reduction and light-shaping slabs can be used with both fluorescent lamps and LED arrays. Simulations help to understand their optical function, but the result strongly depends on a correct modeling of the slab itself. The design details of the structures, however, are typically proprietary to the manufacturers and are, thus, not published.

By measuring the intensity distribution of a luminaire by a goniometer and feeding the data to a light planning software, glare is evaluated for a particular illumination scenario. It should be noted in this context that glare is not a function of the luminaire alone, but instead of the entire illumination scenario. As a luminaire manufacturer strives at fabricating luminaires that allow norm-conformal illumination in many countries and in many situations with as few adaptations as possible, designing of glare reduction and light-shaping slabs is a nontrivial task.

Beyond their refractive function, the surface structures of light shaping and glare reduction reflect a fraction of the incident light, too. This back-reflected light can amount for a considerable fraction of the primary light from the lamps, and the luminous efficiency would be considerably reduced if it was trapped in the system. Thus, many luminaires employ a mechanism known as photon recycling: The fraction of primary light reflected back from the light-shaping slab undergoes a second reflection at the inside walls of the luminaire. To achieve this, reflector sheets with a diffuse total reflectivity of as much as 98% (e.g., Furukawa MC PET [22]) are available. By this diffuse reflection, the angular spectrum of the incident light is re-distributed, such that a major fraction of it passes the light-shaping slab and, thus, contributes to the useful secondary light, as shown in Figure 2. The total emitted luminous flux may, thus, be expressed as a geometrical series, with the reflector's reflectivity being the quantity determining the maximum total emitted flux. It should be stressed that the photon recycling concept is not restricted to luminaire level; rather, it is applied on LED-chip level and LED-package level, too, as discussed above.

Generally, reflectivity of materials is an issue in luminaire manufacturing. Besides porous plastic materials, such as the mentioned MC PET, coated aluminum sheets [23] are widely used. Here, the coating consists of a silver

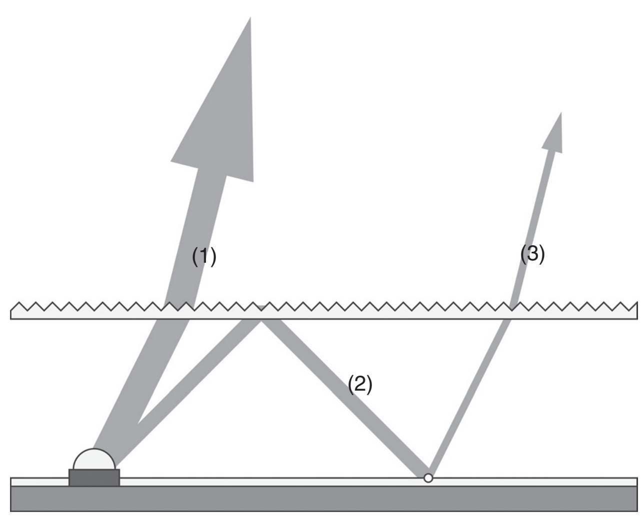

Figure 2 A photon recycling system. A certain fraction (1) of the primary light emitted by the LED is transmitted directly through the light-shaping slab, another fraction (2) is reflected from it. Upon diffuse reflection at, for example, a scattering mirror on the LED substrate, as illustrated here, the angle spectrum of the light (2) is redistributed. By that, it gets another chance to escape the light-shaping slab in the desired intensity distribution (3).

layer plus dielectric layers for obtaining maximum reflectivity in the visible spectrum. Materials of that type are available in different finishes, with different specular and diffuse fractions of the reflected light and are frequently used in all types of traditional luminaire manufacturing. It should be kept in mind here that the reflectivity of these materials does depend on the incidence angle due to their multilayer structure.

Perhaps the most important applications of large-area micro-optics are the field of displays. Displays and luminaires for area lights share two basic concepts, direct backlighting, also known as light box concept (Figure 3), and edge coupling based on light guides (Figure 4). As light propagated in the light guide by total internal reflection, the edge lighting concept requires features to couple the light out of the waveguide in the desired way, i.e., with a homogeneous luminance across the panel. This coupling-out of the propagating light is achieved either by scattering centers within the bulk of the light guide, as in the case of materials such as Evonik End-Lighten PMMA. Other possibilities are screen printing of dots of scattering white color onto the light guide or pyramidal coupling structures on the light guides defined upon injection molding or embossing of the light guide component. For display applications, a number of functional optical sheets are available under names such as 'brightness enhancement foil' (BEF) or 'dual brightness enhancement foil' (DBEF). These foils consist of embossed micro-prism structures with a typical feature size of 50 μm and a typical thickness in the range of 100–200 μm. The purpose of these foils is to increase the intensity in forward direction on the expenses of the intensity emitted to higher angles, which is neither required nor desired in many display applications. Some of the foils even exhibit an anisotropic refractive index to allow for preferential transmission of light of a particular

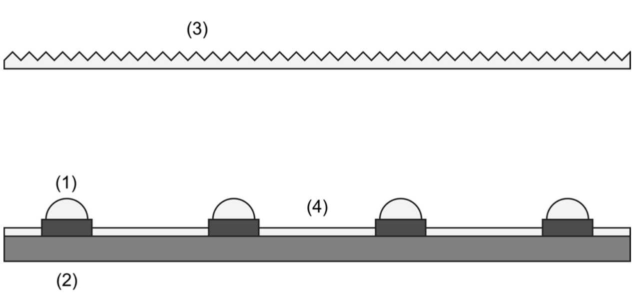

Figure 3 Direct backlighting or light box system. The system consists of a box (2). Typically, the inner walls (4) of the box are coated with a highly reflective material. In many light box systems, high-power LEDs (1) are employed. The optical slab (3) shapes the intensity distribution.

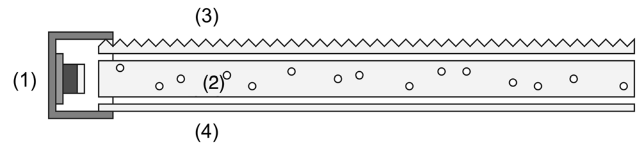

Figure 4 Edge coupling system. Typically, mid-power LEDs are arranged on a linear board (1). The emitted light is coupled to a light guide slab (2) via its edges or corners. Scattering particles in the material or other coupling features on the light guide's surface couple the propagating light out of the slab. Again, the intensity distribution is shaped by an optical slab (3). A backside reflector (4) allows photon recycling.

polarization state to enhance the luminous flux through the subsequent liquid crystal light modulator.

Further recent developments in functional optical foils comprise multilayer optical sheets and luminescence conversion phosphor sheets. Stratified multilayer sheets fabricated from polymer co-extrusion and with a thickness of the individual layers in the range of 100 nm have been demonstrated [24]. Careful adjustment of the thickness of the layers allows even broadband reflection of these multilayers. In the context of blue LEDs, there were several interesting developments of phosphor-containing converter foils during the last years with an application perspective in fabrication concepts of multi-emitter light sources and for novel display architectures. Color gamut is among the most important figures of merit for displays, and thus, recent developments of quantum dot converter foils have attracted particular interest. Large-area micro-optics, thus, appears as an active and vivid field that has already generated omnipresent components and still is open for interesting new solutions.

5 Summary and outlook

To summarize, micro-optical components and fabrication processes have found entrance to lighting applications for essentially three purposes: shaping of the intensity distribution emitted by LEDs, lamps, and luminaires, spatial homogenization of the emitted light with respect to intensity and color, and for light shaping in large-area optical systems, in which the optical elements are to be employed without respect to the exact arrangement of the light sources. By that, there is nearly no LED application without a relation to micro-optical elements or fabrication technologies. Fabrication technologies, including injection molding and embossing, roller embossing, and roll-to-roll fabrication, extrusion, and other fabrication processes for polymer optical components meet the highest degrees of maturity and are routinely applied in industry today. The high quality of these products is even more astonishing given the enormous price pressure on many products in the field.

Beyond that, there are interesting new developments in lighting technology that have directly been influenced by tunable optics as a recent research trend in micro-optics. Here, many tunable components based on the elasticity of silicone rubbers have been conceived, including focus-variable lenses, adaptive mirrors and variable iris stops, and the fabrication technology for liquid silicone rubbers (LSR) has evolved fast. In the field of lighting, these developments may find entrance both for novel fabrication routes, for example, for silicone-on-glass optical components and for tunable lighting systems, for example, spot lights with a variable FWHM angle of the intensity distribution.

By these concluding remarks, it becomes clear that lighting, and in particular LED-based lighting, has profited significantly from technology and research trends in micro-optics. On the other hand, it seems that nonimaging optics, lighting, and illumination have not fully been recognized as important application fields for micro-optics. Thus, it may be anticipated that the influence of micro-optics and lighting may become a mutual one and that this mutual influence helps to overcome the separation of the fields (and mindsets) of imaging and nonimaging optics.

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