Designing Illumination Optics

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Chapter 1

Introduction

In this tutorial, we assume that you are familiar with basic geometrical (i.e., ray) optics, including Snell's law of refraction, total internal reflection (TIR), first-order imaging optics, and spectra. We also assume that you have some experience in illumination optics. However, even if you are a novice, this tutorial will be useful for you, because it will show you a glimpse of many important design methods and elements with which you must get acquainted. If you are an experienced imaging optics designer, this tutorial will be useful for you, too, because illumination design requires a different way to think about light.

We will mostly ignore diffraction, polarization and coherence; and will consider only homogeneous, isotropic, and linear (HIL) materials—i.e., we will mostly ignore gradient index materials, birefringence, and nonlinear optics. These aspects of physical optics are deep and fascinating, but we have so rarely encountered design tasks where they are important that we are limiting the scope of this tutorial to geometric optics and HIL materials.

Although indeed important for illumination design, we will also not discuss color mixing and homogenization in detail: we refer the reader to our recently published tutorial[1] on color mixing.

A growing body of supplementary material, e.g., the optical system files used for the examples, a $\cos^n$ distribution spreadsheet, and more, is available on our website, https://illuminationoptics.net/.

1.1 Motivation

Illumination optics guides light from sources to targets in many different places, industries and environments. In general lighting, reflectors focus beams in spot lamps, and diffusing shells avoid glare in light-emitting diode (LED) retrofits, thus replacing light bulbs and fluorescent tubes. In architectural and street lighting, freeform lenses and reflectors create precisely prescribed light distributions on walls and streets. In automotive exterior lighting, the lamps for forward lighting, daytime running lights, brake lights,

Chapter 2
Preparation

Before we discuss the process and the methods of illumination design, we will introduce some definitions and helpful tools. First, we present what we mean by modeling, simulation and design in our context. We continue with a brief reminder on étendue: the *volume* of a ray bundle in phase space. We decided to keep the section on étendue short, since good, thorough discussions of these core concepts of illumination optics can be found elsewhere.[1,10,11] If you are not entirely familiar with étendue and phase space, this would be a good time to review these references: we cannot overstate the importance of understanding étendue and phase space for successful work in illumination design. The edge-ray principle is discussed next: in summary, it states that rays that start from the edge of a source remain on the edge of the ray bundle throughout the ray path, as long as the optical surfaces are smooth. However, as it is often the case, the details are more complex.

The usual radiometric and photometric quantities are then defined in our context. While many readers may be familiar with flux, intensity, and illuminance, and also with the practical definition of luminance, we find that optics designers often think of luminance as a separate, somewhat disconnected quantity.

However, defining luminance as the density of flux in phase space allows us to make the immensely useful connection between (1) luminance and (2) illuminance and intensity. In passive systems, flux cannot be increased according to energy conservation (the First Law of thermodynamics), and luminance cannot be increased according to the Second Law of thermodynamics (entropy will not decrease).

With the theoretical groundwork laid out, we present a number of useful mental tools, such as light distribution curves, phase-space diagrams (PSDs), luminance diagrams, source characteristic curves, and skewness distributions. We then close this preparation section with a set of example problems, which we will use throughout this tutorial for illustration.

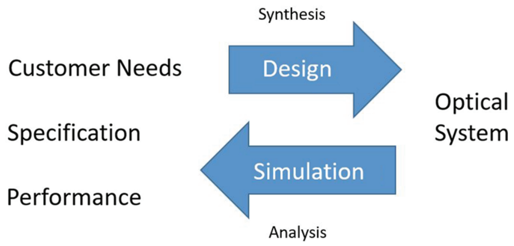


Figure 4 Design vs. simulation.

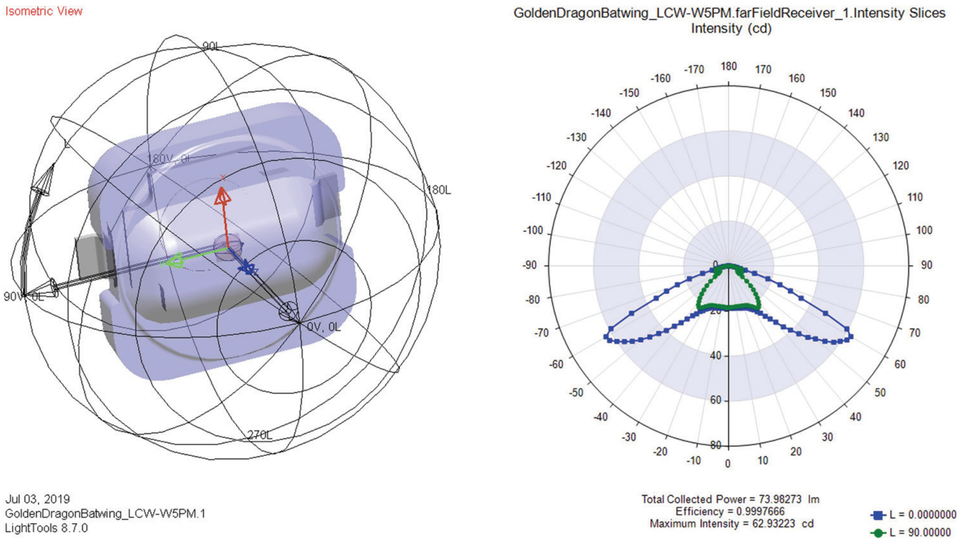
being the transfer of information, not the transfer of energy. Such a point-to-point mapping is allowed, but not required in illumination design. *Nonimaging optics*,[13,14] developed in the context of optimal collection of solar radiation, aims to maximize concentration of sunlight, which can be achieved only with very high NAs, where imaging approaches either fail or become too expensive. In contrast to illumination design, the distribution of light is generally not as important in nonimaging optics. *Lighting design* is a discipline between the esthetic and technical aspects of lighting, creating lighting situations for theater and stage, architecture (interior and exterior) or hospitality. In summary, illumination designers create luminaires, which are then used by lighting designers to create good lighting. Finally, *computer graphics* uses aspects of illumination optics as well; e.g., radiosity for diffuse reflection, and ray tracing and radiometry for rendering purposes. Here, the goal is creating images that look good, or realistic, as opposed to obtaining quantitatively correct results.

All those disciplines feature their own technical framework, modeling techniques, software, mindset, and community. They share the same physical background, but the different targets require different concepts and simulation methods (e.g., *sequential* or *nonsequential* ray tracing, and *radiosity*[15]).

Even the most accurate model does not necessarily imply any understanding of the obtained results and the way to improve them. Especially in the case when performance is limited by conservation laws, only a deeper understanding of the basics will prevent us from being trapped in endless, meaningless, and futile design work. Illumination design does not happen in a computer: it happens in our minds. Knowing how light for illumination works enables us to develop valid ideas that are then tested by simulating a model. Phase space and étendue are key concepts we must understand.

2.2 Phase Space and Étendue

The usual conception of light beams is that they are composed of *rays*. What is a ray? In their classic text book,[16] Max Born and Emil Wolf give this definition:


Isometric View

GoldenDragonBatwing_LCW-W5PM.farFieldReceiver_1.Intensity Slices
Intensity (cd)

Jul 03, 2019
GoldenDragonBatwing_LCW-W5PM.1
LightTools 8.7.0

Total Collected Power = 73.98273 lm
Efficiency = 0.9997666
Maximum Intensity = 62.93223 cd

Figure 10 Light distribution curve / candela plot of an asymmetric batwing LED (OSRAM LCW-W5PM) in type C photometry, showing the C0 and C90 planes (plot generated by a simulation using LightTools).

Illuminance—a function of the location (two variables)—is often shown as a false-color area plot, as a function of x and y, or as a (series of) line plot(s) of cross-sectional values, e.g., as a function of x for constant y.

Luminance, a function of the location and direction (four variables) cannot be shown directly on paper. Two ways are common to show luminance in contour or false-color plots; as a function of the location for constant direction (which corresponds to the output of a luminance camera); or as a function of the direction for constant location (which corresponds to an intensity measurement of a luminaire with a pinhole somewhere in the aperture). Both types of plots are a very instructive way of visually and/or mentally analyzing the output of a light source or luminaire.

Regarding radiant or luminous power distributions, there are two more, less-common, but very useful types of diagrams we introduce: phase-space diagrams (PSDs) and *luminance diagrams*.

2.6.2 Phase-space diagrams

In a system with rotational symmetry, we consider a planar screen $\mathcal{P}$ perpendicular to the symmetry axis (the optical axis). In an analogous way to the general 4D definition in section 2.2, we can now define a 2D phase space. We consider rays propagating in a meridional plane $\mathcal{M}$; i.e., a plane containing the optical axis. Without lack of generality, the z-axis will be the optical axis and the x-axis will be the intersection between $\mathcal{P}$ and $\mathcal{M}$. Hence, such a ray is defined on $\mathcal{P}$ by the coordinate x and the angle θ with the axis.

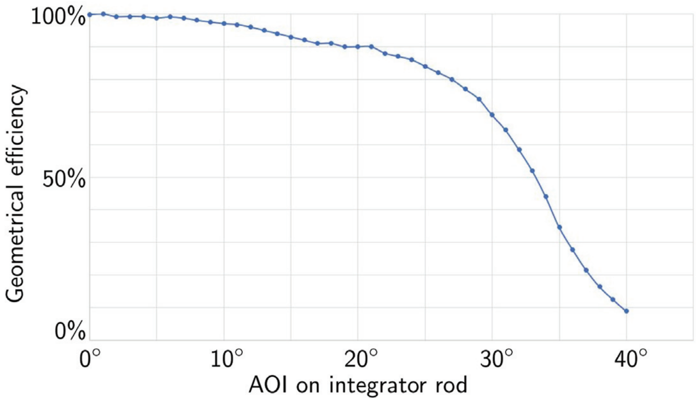


Figure 25 Transmission curve of a DLP projector: geometrical collection efficiency vs. angle of incidence (AOI) on the mixing rod.

beam). This causes a gradual acceptance decrease for higher angles at the rod entrance. We may describe it as target apodization (cf. section 3.3.4).

Including such a curve (Fig. 25) as a filter to the target receiver in the illumination design, a reflector optimization will yield a slightly smaller numerical eccentricity and result in a better efficiency of the whole system. Another interesting aspect is that such a curve may be used to ease the communication between projector and lamp developers by avoiding the necessity to disclose any projection lens details. Instead, the target apodization function carries all necessary input for the light source design.

A final problem remains unsolved: as the arc is close to the optical axis, it can emit only rays with a rather small skewness (refer to References 30–32 and section 2.5), whereas the projector étendue extends to regions with larger skewness.[52] In more detail, an area element close to the rim of the rod entrance face would accept a full cone of light but the arc-reflector system is not able to fill the cone because there are no rays with a suitable skewness. In the course of propagation through the rod, the skewness of rays is randomly altered, leading to a nearly filled cone at any area element at the rod exit area. To deal with such skewness mismatch limitations, breaking rotational symmetry is a promising option, but there are no known reflector designs.

2.7.3 LED searchlight

Task: Collimate the light of a Luminus CBT-140 circular LED to a circular $\pm 1^{\circ}$ beam, with full geometrical efficiency and minimum exit aperture.

Source and target definitions: The source is a circular Lambertian emitter with $r = 2\,\mathrm{mm}$ in air; its étendue is $U_S = \pi r^2 \pi \approx 40\,\mathrm{mm}^2\mathrm{sr}$. The minimum exit pupil size is given by étendue conservation

Chapter 3
Illumination Design Process

Now that we have discussed some theory, defined the most important quantities and analysis tools, and set up a few example problems, we are ready to discuss how optical design for illumination actually works.

3.1 Task Types

In this tutorial, we reserve the term *target* for the entity to which the light is sent: a patch of a receiver area, a screen or wall, or a section of some phase space. A design target will be termed a *goal*.

All illumination design tasks start with some kind of target specification or design goal, which can consist of any combination of radiometric/photometric values, spectral goals, target geometry, source definition, and/or light distribution data. In reality, we often must reach more than one design goal simultaneously, and must balance performance trade-offs accordingly. Of course, high efficiency is almost always requested. In addition, we usually must consider constraints, such as the bill of material budgets, available space, thermal power dissipation, and so on. Often, it is the interplay between optical, mechanical, thermal and electronics problems that render illumination design so challenging—and fascinating. A seemingly small change in the optical system, such as sacrificing only a little efficiency to save cost, may incur a large penalty if the additional electrical power renders active cooling necessary, whereas the more efficient optical system would work with passive cooling.

In fact, illumination design is a prime example where *concurrent engineering*[56,57] is required to achieve globally optimal solutions for the complete product, not just for the optics. Optical designers are well-advised to not simply understand the basics of mechanical, thermal, and electronical engineering, but also to familiarize themselves with concurrent engineering, as a development process. However, in this tutorial we focus on optical design.

Let us assume you are an optical designer, and you are approached with a new design task. You will find that this task is very likely to fall within one of distribution. Quick and easy, often a good starting point, but just as often too simplified for a final design.

- *Physical source model*, which uses some source geometry, optical properties, and models the physics of light generation (e.g., filament luminance by Planck's radiation law,[29] or light conversion in a phosphor element[73]). The details of the model are often difficult to obtain: vendors guard their secrets. Physical source models may represent an ideal source status that is never reached in production.
- *Partially measured* (possibly including some source geometry). Source intensity and/or exitance are measured and serve as a basis for a source model,[74,75] a technique known as *source apodization*. A radiance model such as $L(x, y, \theta, \varphi) = L_{\text{spatial}}(x, y) \times L_{\text{angular}}(\theta, \varphi)$—i.e., assuming angular distribution does not change with location and vice versa—is often an oversimplification.[76]
- *Ray data sources*,[77] regularly provided by light source vendors, are based on measured radiance (near-field goniometry[78]) or on physical simulation (using proprietary information), and provide a detailed and correct representation of a real source. However, the measured data represent the *selected sample* which may not be a typical representative, and simulated data may be idealized or even misleading. Be prepared for large files, a limited number of rays, varying quality, and nontrivial efforts to align ray file coordinates with a mechanical source model, and to assign correct spectra and flux.

There is a lot more to say about source modeling, but it would be beyond the scope of this tutorial to address this subject in detail. To start digging deeper, you may want to consult the webinar in Reference 79. In any case, we emphasize our prior comments on model *validation*. Compare simulated vs. measured intensity distributions. Compare a simulation of an image of the source with an actual image (an old mechanical wide angle photography lens creates great images of bright sources). Validate, and take care when you use a source model outside of its validation range!

3.3 Target or Receiver Aspects

3.3.1 Standard target

The archetypal target definition is *a suitably located surface, featuring an acceptance angle definition*. In the 2D PSD (section 2.6.2), this corresponds to a *rectangle*, and the design task is to transform the source phase space in a way that the obtained distribution is inside this rectangle. This task can be tricky, even if the étendue of the source is smaller than that of the target or if the phase-space shape of the source is the same as that of the target. Aberrations may alter the shape of an originally ideal distribution and prevent us from efficient collection[80] (section 4.6.6).

end of the chain.[86] However, if the imaging subsystem is known, it may be advantageous to include it into the simulation, simulate the object plane with reasonable scattering properties and simply look for the light distribution and illuminance on the camera chip itself.

3.3.5 Virtual target

Sometimes we must deal with virtual targets: planes that the final rays never actually intersect, because these planes are located within or even behind the illumination optics. One example is a source expander, useful to reduce the angular extent of a Lambertian source by increasing the source's area, or to increase source étendue in a controlled way [e.g., in an automotive head-up display (HUD)]. The imaging community is familiar with the *Bravais system*,[87] whose effect is rather equivalent.

In the examples of Fig. 34, we chose to locate the virtual image (or non-image) of the source in the same plane as the source itself. In the first design, we expand the diameter of the Lambertian source by a factor of 4, into a nearly telecentric beam. We achieve this by first collimating the light into a telecentric $\pm 30^\circ$ beam with a solid dielectric θ_1-θ_2 converter,[2,10] and then we image this telecentric beam with a suitable singlet lens from infinity to the desired virtual target plane. Our second example uses the obvious design element from nonimaging optics, the CHC.[10,88] Both systems are geometrically 100% efficient.

3.3.6 Variable target

A last type of illumination designs tasks is characterized by a variable target, requiring a *tunable* illumination system. Such systems are termed *zooms* (e.g., in the entertainment field), and may indeed comprise real zoom optics. However, there are many more possible solutions, and thus we prefer to term them *variable beam* designs. In section 5.3 we provide an overview of possible solutions.

3.4 Initial Design Considerations

We are now ready to discuss what to do, once an illumination design task arrives. The first step is a critical look at what the customer specifies. (We use customer in a broad sense: an external customer, your boss, your marketing team, even yourself.) Usually, extracting meaningful and complete information from customer data is required. Exact terms are needed to compute e.g., luminance, and source and target étendues must be calculated from geometrical data. It is always good to develop a deep understanding of what the customer actually needs, as opposed to what the customer requests. If you understand the final application, you may well be able to help the customer in unexpected ways.

Chapter 4

Illumination Design Methods

There are many ways to carry out the actual design work. You may use simulation software on a computer, construct lenses on paper, solve differential equations analytically or numerically, bend metal by trial and error, and more. Designs may be simple or sophisticated. We prefer simple designs, which tend to be more challenging. The simpler the design, the more optical functions per surface. Sometimes, even shortcomings of an optical system (such as vignetting, distortion, or coma of a conic) can be used as a feature to generate (aspects of) the desired distribution.

This section is intended to give a short overview of illumination design methods and to classify them by the nature of the problem to which they are applied. The reality of, e.g., industry segments, markets, applications, design methods, source and target classifications, and degrees of étendue limitation is too complex to be organized in a 1D tree structure. Accordingly, we may look at this landscape from several vantage points. Even if you happen to work in a specific industry segment, it is valuable to consider this metaphor: look over the fence to see which interesting plants might grow in your neighbor's garden, and how you might adapt them to your ecosystem.

More about certain methods can be found here:

- reflector design[92–94]
- nonimaging optics[2,10,90]
- freeform design methods[95]
- homogenization.[1,67]

4.1 Taxonomy by Task or by Étendue

Let us start by looking at a selection of typical systems in various industry segments. Most illumination optics are designed in automotive (exterior and interior), consumer electronics, entertainment (stage, studio), general and architectural illumination, medical, and professional lighting (dedicated task lights for professionals or machine vision). In Table 1, we compiled a assuming that only a single infinitesimally small freeform surface element is responsible for each point at the target. Finite sources violate this assumption. If the violation is not too severe—i.e., only a small fraction of the freeform surface appears flashed from each point of the target screen—there is a good chance that a good solution can be obtained by treating the finite source size as a perturbation. One would tailor a freeform surface using the actually desired target distribution, simulate the influence (the blur) of the finite source size, and modify the target distribution in order to correct for the perturbation.[126] However, there are important cases where the size of the optics is limited by the luminance of the source. For automotive headlamps, LED street lights, mobile phone flashes, wall washing luminaires, and more, there may be a peak illuminance location from where the *whole* freeform surface must look flashed in order to achieve this desired peak illuminance, given the finite luminance of the source and the limited space for optics. In these cases, the point-source tailoring approach yields poor results, or simply breaks down. Non-perturbative extended-source tailoring methods, briefly described in section 4.4.2, would address these problems appropriately, but are still in their infancy and not commercially available.

Finally, we mention that while a single freeform surface can fully control the *illuminance* distribution on a target surface, we have no control over the *phase* at the target surface, which comes out as a result. In laser beam shaping, this is not acceptable: phase must be controlled, creating a planar wavefront with the desired irradiance distribution. A simultaneously tailored second freeform surface is required to reconstruct the wavefront.[124,127] When the wavefront deviation from planar is small, however, the problem separates. First, a surface is tailored to create the desired distribution on the desired wavefront plane; and second, a nearly planar generalized Cartesian oval (refer to section 4.2.1) is calculated, perfectly compensating the wavefront error while disturbing the illuminance only slightly (and iterative correction can be employed to compensate).

4.3 Edge-Ray Methods

In section 2.3, we introduced the *edge-ray principle*, and now we consider methods using it. As a reminder: edge rays are the rays that form the 3D boundary of a 4D ray bundle. Consider a ray bundle as it intersects a certain screen (refer to section 2.2 for what we mean by *screen*). There, the edge ray set typically consists of two subsets: (i) the spatial edge rays, from the spatial rim of the ray bundle's footprint on the screen into any direction; and (ii) the directional edge rays, from anywhere on that footprint to or from some limiting edge somewhere else, maybe a lens aperture or a baffle. The edge-ray principle indicates that under the usual conditions for étendue conservation (no ray splitting, no scattering, no wavelength conversion, and smooth

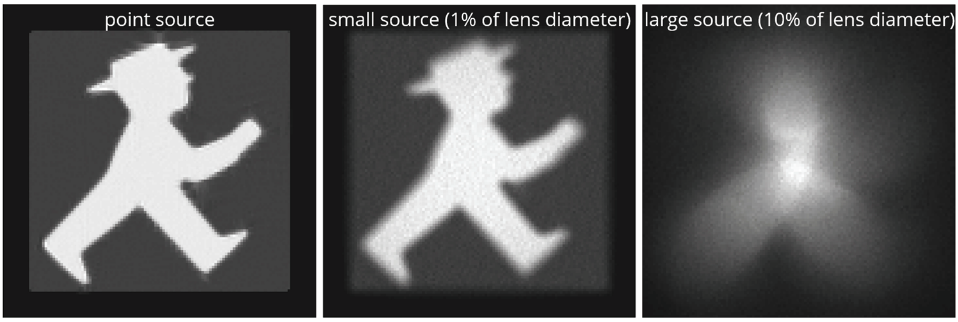


Figure 47 Simulation results for the freeform lens shown in Fig. 39, with varying source size. Left: the nearly perfect result for the point source. Center: the source has a diameter of 1% of the lens, and visible blurring occurs. Right: with the source size being 10% of the lens diameter, the lobes hint at legs, arms and a head, but all details are lost.

entirely. Other intrinsically non-point-source approaches are required. This is the case for the right-hand image in Fig. 47.

Unfortunately, there is not much progress on the research side regarding exact methods for extended sources. An exception is the 3D SMS method (section 4.3.4), invented by Miñano and Benítez.[90,135,143] Here, two freeform surfaces are tailored simultaneously to guide two wavefronts from the source in a desired way. This method can correct for finite source size to first order even if the source is relatively large. However, as already noted, there appears to be no commercially available software that has implemented the SMS method. Other researchers have published some promising results, notably Brand and Birch,[146–148] and Sorgato et al.[149] We consider these approaches promising, but hard to implement by oneself, and unfortunately, we are not aware of any commercial implementation. The only well-established and commercially available tailoring method for extended sources is the iterative perturbation approach,[150] available in LightTools software.

4.5 Phase-Space Transformation Techniques

Fundamental laws prevent us from doing magic and increasing radiance in passive systems. However, we may *transform the phase space* and shape the étendue of the source in a way that matches the target shape. The idea is that for a given target étendue $U = \text{constant}$, the shape of that phase-space volume provides additional degrees of freedom.[63,151] The IODC illumination design problem of 2006[58] (asking for a square-to-cross transformation) is a good example.

4.8.1 Introduction

We start with a literature review in an attempt to classify aspects of illumination tolerancing:

- Nonimaging collimators/concentrators: shift and tilt investigated by simulation,[220] shape deviations, and tracking errors investigated by ray path statistics calculated analytically.[221]
- Freeform lenses with surface perturbations, investigated by simulations.[222]
- Reflector shape sensitivity, consideration of one surface point, and simulation.[220]
- Automotive lens systems investigated by matrix optics.[223]
- Figure errors of a freeform beam shaper discussed in terms of the original differential equations.[224]
- Uniformity of a DLP illumination system, Monte Carlo tolerancing, use of compensators.[225]
- Uniformity of a Köhler system.[225]
- LED and freeform lens, tilt and decenter.[226]
- TIR lens shape.[227]

In imaging design, tolerancing means varying relatively few types of design parameters (curvature and thickness) and mounting parameters (tilt/decenter), while keeping the merit function stable. In illumination design, with ubiquitous injection-molded and deep-drawn parts, and light sources with varying properties (unstable arcs and LEDs from various bins), more types of parameters influence the performance compared to imaging design. In the world of reflectors and TIR lenses, we must consider manufacturing deviations from molding to assembly rather than the originally used design parameters. Surface quality plays a major role for systems generating collimated beams. Such tolerances are often hard to model and to quantify. Compared to imaging, tolerances themselves tend to be much more relaxed, while the tolerancing *process* tends to be more difficult.

4.8.2 Types of tolerances

We must consider:

- Element positions (assembly deviations): decenter and tilt
- Element geometry deviations
  - by dimensional parameters; e.g., thickness
  - by surface shape deviations
- Deviations of surface and bulk properties (absorption and scattering)
- Source deviations other than position

There may be *alignment steps* in the production of illumination devices that must be taken into account analogously to *compensators* during tolerance analysis. For example, focal length deviations of an elliptical reflector may be superposition or envelope of all these influences and given to the manufacturer. This may well be inadequate: performance of illumination optics depends more on slope and curvature deviations than on spatial displacement. Unfortunately, there is no established method of specifying such tolerances in illumination optics. We often rely on working directly with the manufacturer, defining a manufacturing process that is proven by trial and error to work well.

4.8.3 Source tolerances

Differences between real sources and sources in the model are just as important as tolerances of optical elements. First, Monte Carlo ray-tracing noise is unavoidable and must be taken into account. A good way to estimate the amount of noise in performance values (the noise floor) is to repeat the simulation with increasing number of rays and evaluate the convergence (cf. Fig. 61).

When we use a ray file for illumination design, we always conduct a final detailed analysis of the ray file;* e.g., by reversing the ray directions to determine if we can find expected structures in the source. Larger ray files help to avoid Monte Carlo noise. When time and budget permits, several near-field goniometer measurements with several samples of the same source type can greatly help to assess source-to-source variations. Sometimes, dimensional tolerances in data sheets can be used as a starting point for positional tolerances, on top of the typical 50 to 100 μm placement tolerance on printed circuit boards.

For LEDs, binning is an important aspect.[229] Of course, the flux of a single LED will simply scale the result. However, flux will vary between LEDs in a multi LED system, and LEDs from different wavelength bins may cause a different interaction with a dispersive optical system.

4.8.4 Tolerancing procedures

Analogously to imaging optics, two basic evaluation techniques[230] are available.

Sensitivity analysis: The variation of one parameter at a time shows the sensitivity of the results to this one parameter. The results may be used to tighten or to relax specific tolerances. However, interactions between different tolerances are neglected. We can possibly use data that were stored during optimization runs.

Monte Carlo analysis:[231] Simultaneously and randomly varying all design parameters and other variables, in a large number of trials, can provide a realistic forecast of the production results (Fig. 67). Here, it is important to

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*One of the authors remembers an early discharge source ray file where the electrodes were not collinear.

Chapter 5

Design Patterns: Building Blocks for Illumination Systems

Illumination optics deals with the task of capturing light from a source and *transforming* it in a way that delivers what is desired at the target. Sometimes this transformation can be accomplished with a single optical element; at other times, a complex combination of several elements is required. Either way, it is very rare that something uniquely new is invented. Most of the time, we reuse, modify, and combine known solution approaches for the transformation (sub)tasks. We term these building blocks *design patterns*[234] (a common notion in software engineering); and we think of them as an architect does when creating a building, by reusing, modifying, and combining elements such as foundations, walls, windows, and many more.

Unfortunately, describing a full collection of design patterns in detail is beyond the scope of this tutorial. Such a collection is more than sufficient material for a separate book (one that we are writing). Here, we only provide a list of some important design elements and patterns, with references to the literature for further reading.

5.1 Illumination Systems

The ubiquitous sequence of functions and elements in an illumination system is: source → collimation → beam shaping → beam delivery → target (Fig. 68).

These function blocks consist of one or more *design elements* that are created using the methods described in the preceding sections, perhaps even available from stock,[235] and adapted to the specific application by its design parameters and manufacturing technologies.

Ideally, an element fulfills more than one function; e.g., an elliptical reflector collects the light from an arc lamp and delivers it to a target in its secondary focal plane, or a TIR lens collects the near-axis rays from an LED via the central lens, and the high-angle rays via the outer TIR ring, collimating everything into one beam. Sometimes, condenser and collimator elements can

Chapter 6
Summary

Nearly every person who designs optics for illumination is a side entrant, from disciplines such as physics, mechanical and electrical engineering, classic imaging optics engineering, mathematics, and computer science. One of us (Henning) studied physics and worked in imaging optics before joining a lamp manufacturer. The other (Julius) is also a physicist and came across illumination optics via concentrating sunlight and then reversing the light path. What we both found is that at first glance, illumination optics seemed simple, almost too trivial for an accomplished scientist or engineer. Upon a more detailed examination, the subject became more fascinating and we started to appreciate the depth and beauty of the science and mathematics involved. After decades in the field, we still discover new connections, applications, and insights. The most important aspect for us is that the deep, beautiful theory is immediately and readily applicable to the practical needs of various markets. We simply love it when a design that requires some deep insights is successfully put to good use in actual practice. In this tutorial, we hope we conveyed many of the lessons we learned over the years to our readers.

Henning Rehn, a physicist, graduated from Friedrich-Schiller-University Jena 1991 and received a Dr. rer. nat. in Applied Optics there in 1995.

After some years as a post doc scientist he started an industrial career at Carl Zeiss, Jena developing some of the early data projectors.

In 2001, he moved to OSRAM for projector lamp development. Later, he also worked as a group leader in pre-development and LED based specialty products and from 2013 as a Principal Key Expert for optical design.

In 2018, he moved to Switzerland to join FISBA and became a team leader of the optical design group.

Henning authored over 40 scientific papers and about 50 patents.

Julius Muschaweck, a German physicist, has been working on optical design for illumination for over twenty-five years. After a stay as Visiting Scholar at the University of Chicago with Prof. Roland Winston (well known as the originator of Nonimaging Optics), he was co-founder and CEO of OEC, an optical engineering service which pioneered freeform optics for illumination. Later, at OSRAM, where he held the position of Senior Principal Key Expert (the highest rank in the Siemens/OSRAM expert career), he coordinated the over 100 optical designers within OSRAM world-wide. He then joined ARRI, the leading movie camera and lamp head maker, as Principal Optical Scientist. Julius Muschaweck now works as an independent consultant, providing illumination optics solutions to industry clients, teaching courses on illumination optics, and writing about the subject. He is the author of over 25 scientific papers and the inventor of over 50 patent applications. He also loves to go hiking with his wife and their dogs.