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Introduction

1.1 Overview of LED Lighting

Solid-state lighting is a new type of lighting technology based on the high power and brightness of LEDs (light-emitting diodes), and it is commonly known as *LED lighting*. LED is a semiconductor luminescence device based on the P–N junction electroluminescence principle. Compared with conventional light sources, LED has advantages such as low power consumption, high luminous efficiency, long lifetime, compact size, low weight, high reliability, and being environmentally friendly; it is regarded by the industry as the twenty-first-century green light source as well as a future developing trend in lighting technology, possessing great market potential.[1–5]

For the past two centuries, natural and energy resource consumption by human beings has increased, and the corresponding environmental pollution and ecological damage have drawn much attention. Reducing energy consumption and adopting energy conservation and environmental protection products are becoming common beliefs of international society. Lighting alone consumes around one-fifth of the total electricity generated globally. In the current energy shortage situation, adoption of energy conservation and environmentally friendly LED-lighting products is meaningful for conservation of energy and reduction of petroleum imports.

To cope with development trends of the semiconductor lighting industry, the United States, the European Union, Japan, and China have given high priority to LED as a primary and strategic industry. They have unveiled their national solid-state lighting plans and devoted huge labor and material resources to research and development (R&D). Take the United States as an example: in 2000, they promoted the National Solid State Lighting Research Program, which invested $500 million for the development of the solid-state lighting industry from 2000 to 2010. In July 2000, the European Union constructed the Rainbow Project, which grants commissions by six large companies and two universities to promote the application of LED. In 2003, China launched the National Solid State Lighting Project. China also announced officially in 2006 that the Solid State Lighting Project will be included in the Tenth Five-Year Plan, and China expected to invest 350 million RMB for semiconductor lighting technology development and promotion. In 2010, solid-state lighting was listed as one of the most important strategic emerging industries in China; there are nearly 30 research institutes and more than

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2000 companies nationwide that will focus their research and development on LED lighting related to epitaxial growth, chip fabrication, packaging, and application. In the meantime, the world's three lighting giants, General Electric (GE) in the United States, Philips in the Netherland, and OSRAM in Germany, not only established respective solid-state lighting divisions or subsidiaries, but also carry out a wide range of global cooperative efforts and strive to seize the high ground of the future market.

Under the government's strong support and guidance, as well as large investments in R&D from both institutes of companies and universities, solid-state lighting technologies (including epitaxy growth, chip manufacturing, and packaging technologies) are developing very fast, and the performance of LEDs is increasing dramatically. The luminous efficiency of an LED module reached more than 300 lm/W in the lab[6] and 150 lm/W in the market in 2014, much higher than the luminous efficiencies of most traditional light sources (e.g., 15~25 lm/W for incandescent, 70~100 lm/W for fluorescent, and 100~120 lm/W for high-pressure sodium) and creating significant energy saving of more than 50% for lighting power consumption. Moreover, with rapid improvements in the cost-effectiveness of LED packaging modules and application products, the global solid-state lighting market is growing rapidly. Take China's LED-lighting market as an example. In 2014, the gross output of the LED industry of China reached as high as 344.5 billion RMB (about US$55.1 billion), an increase of 30.6% compared with the gross output in 2013 of 263.8 billion RMB (about US$42.2 billion).[7]

In Figure 1.1, high-power LEDs have been vigorously developed in general lighting and specialty lighting applications. For example, through the 10 City 10,000 Lamps project, LED road lighting and LED tunnel lighting are currently being promoted nationwide in China. LED-backlighted cell phone screens, computer monitors, and large-size TVs are gradually becoming familiar to a huge number of families. Emerging LED automotive headlamps and LED-based pico-projectors are under rapid development. A variety of LED lamps for indoor lighting (e.g., LED bulbs, spotlights, downward lights, and panel lights) are applied in commercial lighting, factory lighting, office lighting, museum lighting, house lighting, and other lighting occasions to get more and more applications. Also, LED lamps also are widely used in urban lighting, military and police special lighting, and other occasions for a large number of applications.

The solid-state lighting industry chain includes upstream LED substrate material, epitaxy growth, chip design, and manufacturing; midstream includes LED packaging and testing; and downstream is reserved for specific applications, including LED general lighting and special lighting as shown in Figure 1.2. The ultimate LED lighting product performance is closely correlated with every aspect of upstream, midstream, and downstream: from epitaxy growth, chip manufacturing, packaging, and testing to application product design and manufacturing, where each process step will exert important impacts on the system's lighting efficiency, the lighting quality, and the reliability of LED lighting products. In the meantime, for a high-power LED manufacturing process, each process step is interrelated that will have a coupling impact on LED output efficiency, reliability, and so on.

Therefore, solid-state lighting technology is a combination of the semiconductor, physics, optical, thermal, mechanical, materials, electronics, and other interdisciplinary research fields. For LED packaging and applications, optical design, thermal design, drive control, and reliability are the four key factors. Among them, the lighting performance is the ultimate design purpose of LED lighting, and good heat dissipation

Figure 1.1 Diverse applications for high-power LEDs.

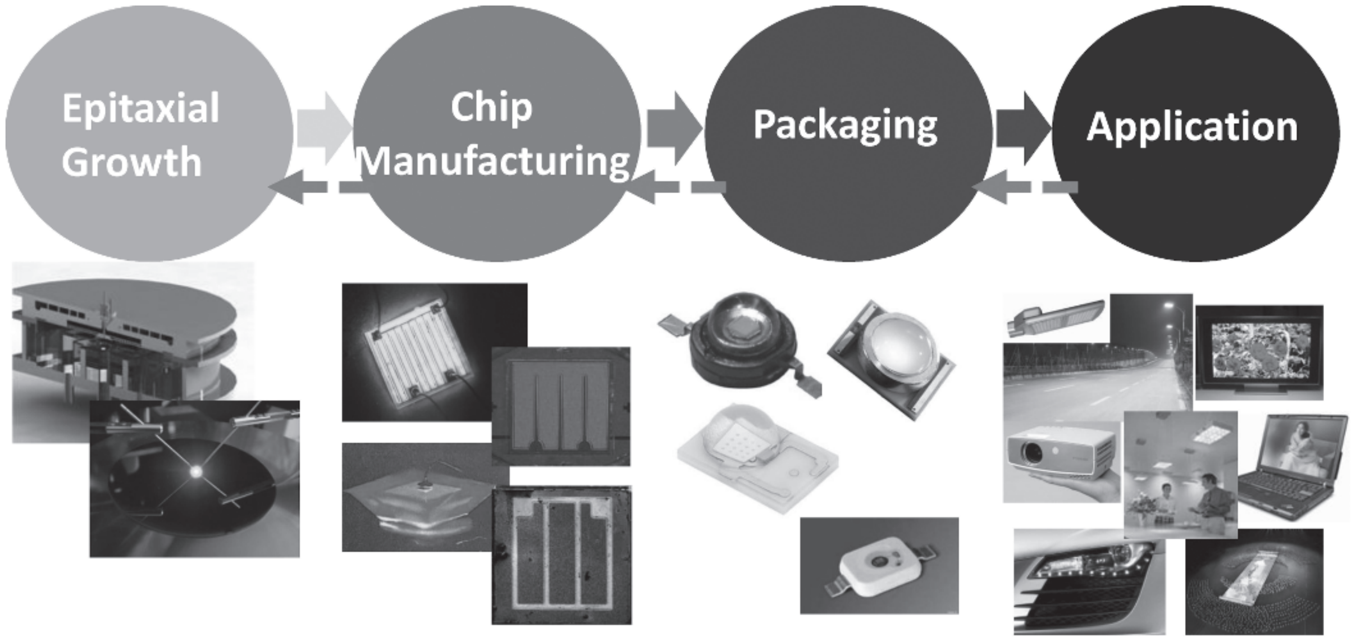


Figure 1.2 Schematic of an industry chain for high-power LED manufacturing.

and high reliability design offer a guarantee for long-life LED lighting products. Moreover, in the LED industry chain, packaging is the key connecting link between the upstream and downstream, and application is the major driving force for the whole LED industry. According to GG-LED, the gross output of LED packaging and applications accounts for more than 90% of the total LED industry's gross output.[7] This book will focus on the emerging freeform optics technologies for LED packaging and various applications.

1.2 Development Trends of LED Packaging and Applications

To gain a better understanding of the design concept of freeform optics, which will be discussed in later chapters in this book on LED lighting, we will first have a brief introduction to the development trends of LED packaging and applications in this section.

As shown in Figure 1.3, brighter, smaller, smarter, and cheaper are always the development trends of LED packaging. With the rapid development in the last decade of LED chip manufacturing, such as patterned sapphire substrate (PSS) and thin film flip chip (TFFC); LED packaging materials, such as direct plated copper (DPC) ceramic, white epoxy molding compound (EMC), and high-stability silicone; and LED packaging processes, such as wafer-level packaging (WLP) and chip-scale packaging (CSP), the performance of LED packaging modules, whatever their luminous efficiency, thermal stability, or reliability, has improved significantly. For example, the largest size of a 1 W high-power LED packaging module based on a metal lead frame was over 10 mm in 2006. However, with the emerging flip chip and CSP technologies, one LED packaging module measuring 1.5 × 1.5 × 1.4 mm in size was able to emit more than 220 lm light when driving by typically 700 mA, and it could reach 300 lm by a maximum of 1000 mA in 2014.[8] Therefore, freeform optics should be integrated with LED packaging modules to achieve a new kind of application-specific LED packaging (ASLP) module that can be adopted directly in various LED applications to meet illumination requirements without large-sized secondary optics. Moreover, with the size decrease of LED packaging modules, more compact freeform lenses should be

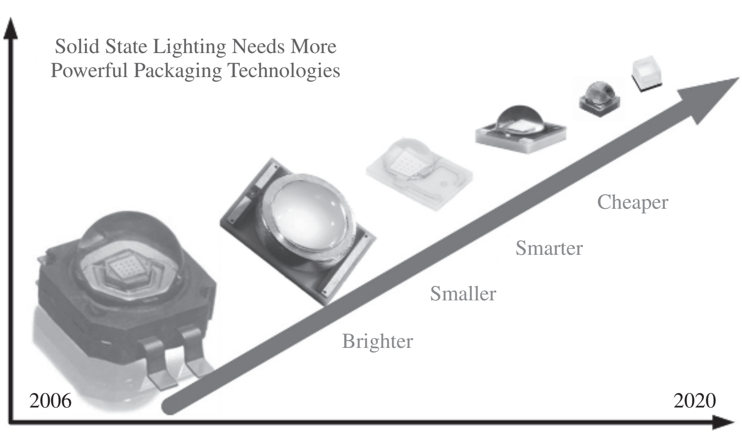
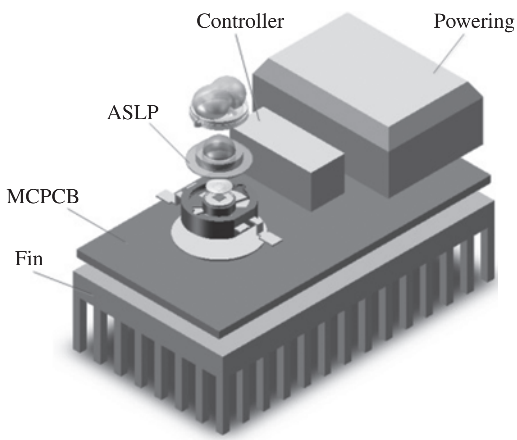


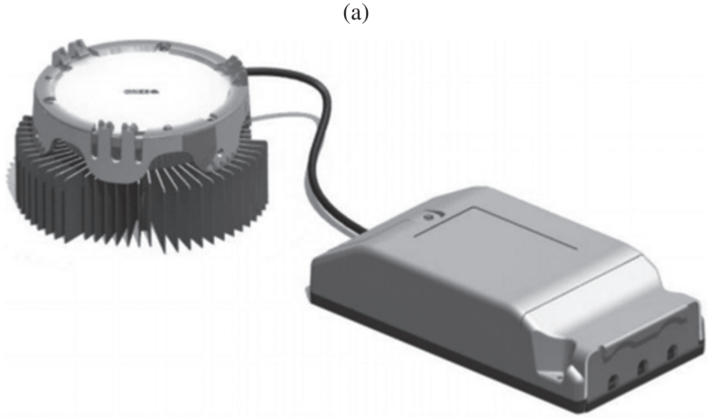
Figure 1.3 Development trends in LED packaging.[1]

designed for new-generation LED packaging, which requires improved freeform optics algorithms to deal with the extended source problem to achieve good illumination performance. In this book, these emerging and key issues of freeform optical design for new LED packaging will be presented in detail.

For LED applications, the standardization of an LED module is the key issue to promote the wide application of LED lighting worldwide. The standard LED light module, also called the *LED light engine*, is integrated with functions of a high-luminous-efficiency LED light source, precise optical design, efficient heat dissipation, power driving, and intelligent control; it is widely recognized as the trend of LED applications and has developed rapidly in recent years.[1] Figure 1.4 shows the design concept of the LED light engine and some LED modules released by CREE.[9] Freeform optics design methods mentioned in this book will follow this development trend to meet the demands of the fast-growing LED industry. Moreover, specific LED light engines integrated with freeform optics for applications of LED road lighting, LED automotive headlamps, and LED backlighting of liquid crystal displays (LCDs) also will be demonstrated in this book.



(a)



(b)

Figure 1.4 (a) Design concept; and (b) CREE LED light engine.[1,9]

1.3 Three Key Issues of Optical Design of LED Lighting

For LED lighting, an LED lamp's illumination performance is the final objective that people see and feel, so optical design is very important for LED lighting. There are three key issues in optical design of LED lighting: high system luminous efficiency, a controllable light pattern, and uniform spatial color distribution. High luminous efficiency is the most fundamental issue of LED sources and lamps to achieve great energy saving. A controllable light pattern is the most basic as well as important issue to meet the requirements of various LED lighting applications with different specifications. In addition, besides efficiency, recently people have paid more attention to the comfort level of LED lighting sources. High spatial color uniformity (SCU) will enhance the comfort and the lighting experience of LED lighting significantly.

1.3.1 System Luminous Efficiency

In order to realize optimized LED illumination performance, effective and efficient optical design is indispensable. The system luminous efficiency (lm/W) of an LED illumination luminaire is a very critical factor in optical design. Due to the fact that the cost per lumen for LED sources is still higher than that of some conventional sources, improvements in the system luminous efficiency of LED lighting devices can reduce the number of LEDs in use, lower system costs, and improve the competitiveness of products. The system luminous efficiency (lm/W) of an LED illumination luminaire is the product of the LED package module's luminous efficiency (lm/W), the system optical efficiency of the lighting device, and the efficiency of driving power. Among them, the luminous efficiency of an LED package module is influenced by LED chip design, phosphor material selection, the package lens, the lead frame, board surface reflectivity, and so on.[1,10] System optical efficiency is affected by the optical efficiencies of optical components (e.g., lens and reflector) within the illuminating system.[1]

In this book, we first introduce the concepts of primary optics and secondary optics in LED lighting. Primary optics is the optical design that is closely correlated with LED packaging modules, including the LED chip and package material coupling light output, the lighting property of phosphor, the packaging lens, and so on. At the same time, it also includes LED chip microstructures on the top surface with collaborative design for the packaging process and integrated design for the packaging lens and secondary optics. The quality of primary optics design directly affects the LED packaging module's luminous efficiency. Secondary optics, in contrast, includes the optical design except for the LED package module–related optics. Typical examples include reflectors, lenses, and diffusers in an illumination system. Note that the system efficiency of an illuminating device is determined by secondary optics, not only the light output efficiency of the secondary optics element itself but also accurate light pattern control to reduce light waste in lighting applications. The discussion range of this book mainly focuses on both the packaging primary optics lens design and secondary optics design in LED illumination applications.

1.3.2 Controllable Light Pattern

For LED illumination luminaire design, precise control over light pattern is another critical factor. Generally, the spatial light intensity distribution of an LED packaging module

Figure 1.5 Illumination performances for LED road lighting with a (left) circular light pattern and (right) rectangular light pattern.

is very close to Lambertian, which will generate a circle-shaped light pattern. This light pattern has a nonuniform illuminance distribution that decreases with $cos^4\theta$ from the center to the edge. Uniform illumination is required in many lighting applications. Due to the nonuniform nature of LED light intensity distribution, LED packaging modules usually should be combined with a secondary optics design. Therefore, whether the light pattern of an LED illuminating device can be controlled directly results in whether we can achieve functional LED lighting such as a uniform circular light pattern, uniform rectangular light pattern, automotive low-beam with a special light pattern, and the like. Figure 1.5 shows a comparison of LED road lighting performance. On the left-hand side, it shows the LED road lighting illumination performance with a circular light pattern, which has spots of light and dark pavement staggered with lower uniformity. On the right-hand side, it shows the LED road lighting illumination with a rectangular pattern, and the pavement has bright uniform lighting effects that are much better than the performance shown on the left.

1.3.3 Spatial Color Uniformity

Currently, white-light high-power LEDs are mainly realized through high-power blue light emitted from GaN LEDs stimulating the yellow phosphor. With the efficiency improvement of LED chips and phosphor, the luminous efficiency of commercialized LED packaging modules has reached 150 lm/W and 300 lm/W in the laboratory, which is much higher than that of conventional lighting, and the energy-saving advantage is obvious. However, with the promotion of LED lighting, especially for outdoor lighting applications such as road lighting and tunnel lighting and indoor lighting applications such as bulb light and down light, customers have set high standards on the quality of LED lighting performance in both brightness and spatial color uniformity. The drawback of the spatial color nonuniformity of LED packaging modules is revealing, and it is one of the bottleneck problems hindering the further promotion of LED applications. Figure 1.6 shows the light pattern of a high-power LED in the market

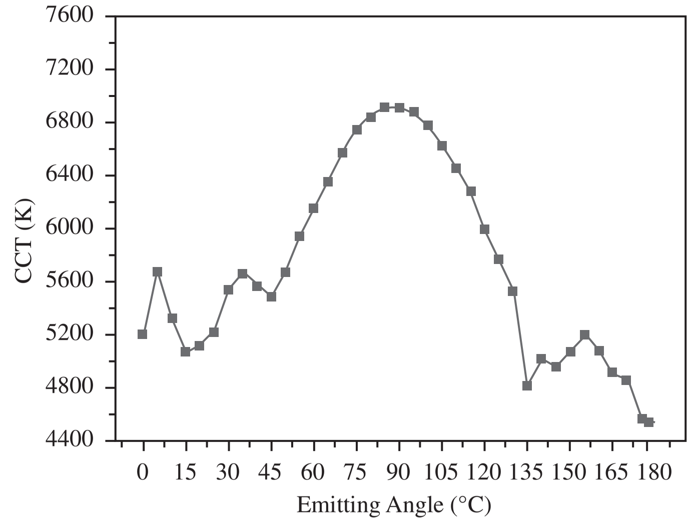


Figure 1.6 Nonuniform light pattern of a high-power white LED and its correlated color temperature distribution.

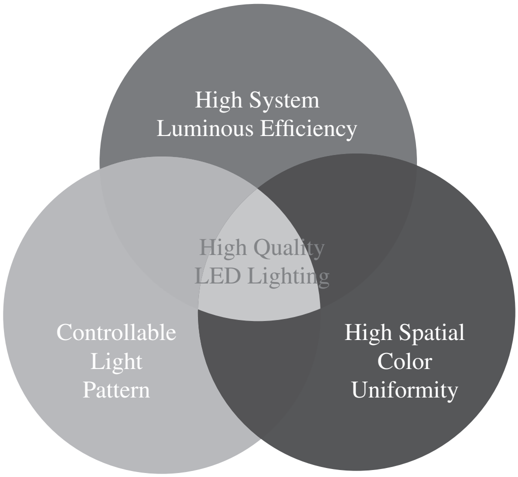


Figure 1.7 Three key optical issues for LED lighting.

manufactured by a famous LED company. We can find that both the light pattern and the color are not uniform: there are obvious yellow rings at the edge of the light pattern, while in the center the color is bluish, which shows the low spatial color uniformity of LEDs emitting light. The uniformity of correlated color temperature barely reaches 67%. Low quality of illumination and color uniformity is acceptable for outdoor application, but for indoor lighting application or backlighting application, this will generate visual error and discomfort and will not meet the standard requirements, which greatly limits the application of LED lighting.

From the above analyses, we can find that high system luminous efficiency, lighting pattern controllability, and high spatial color uniformity are the three key issues to realize high-quality LED lighting, as shown in Figure 1.7. LED optical design research is carried out in these areas, and this will help to improve LED lighting performance to satisfy a number of functional lighting application demands and to promote the popularization of LED lighting and wide application of great significance.

1.4 Introduction of Freeform Optics

There are several ways to address the three key issues of optical design of LED lighting mentioned in this chapter. Most important is choosing a proper and powerful way to create optical designs for various kinds of LED packaging and applications. For example, a rectangular light pattern can be achieved by combining multiple reflectors with different inclined angles. However, is it the most efficient, compact, and convenient way?

Freeform surfaces are those that cannot be expressed analytically and are not suitable for description in uniform equations, as shown in Figure 1.8. Freeform optics, including reflectors and lenses, based on freeform surfaces was first developed for concentrated solar power in the 1960s.[11] Freeform optics is an important means to realize nonimaging optics. Freeform optics is able to redistribute lighting energy, and it has advantages such as high light output efficiency, accurate light irradiation control (shape of light pattern, uniformity, etc.), high design freedom, compact size, convenient assembly, and so on.[11–23] Readers will become aware of these characteristics gradually after reading the

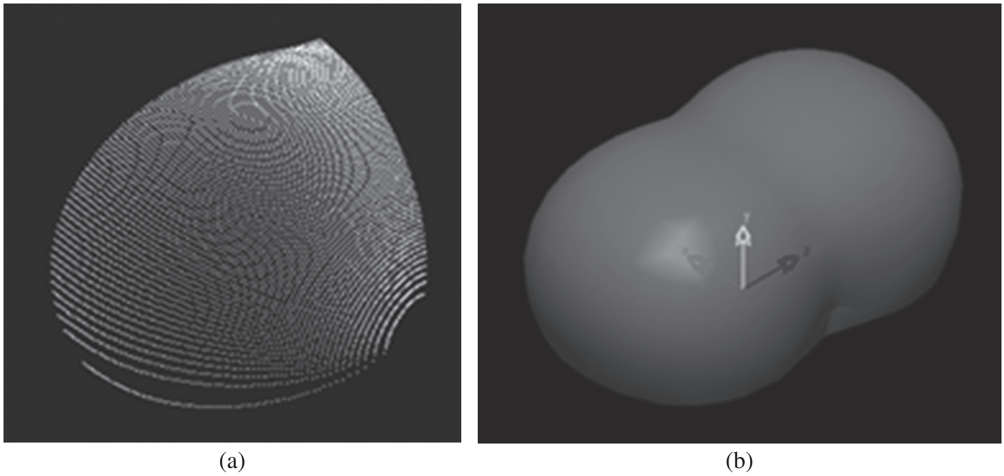


Figure 1.8 Schematic of freeform optics.

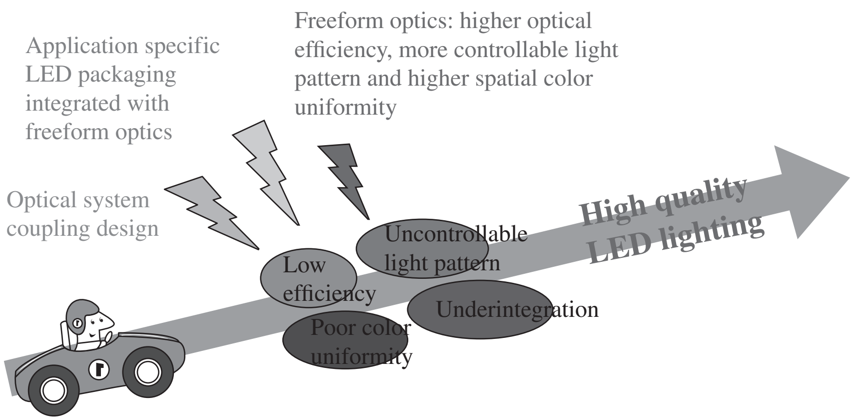


Figure 1.9 Freeform optics as an emerging optical design method for LED lighting.

chapters in this book about freeform optics algorithms and design methods. With these advantages, as shown in Figure 1.9, freeform optics becomes a powerful and advanced solution to overcome problems existing in LED lighting, such as low system efficiency, uncontrollable light pattern, poor spatial color uniformity, underintegration, and so on, and to achieve high-performance and high-quality LED lighting.

With the rapid development of LED lighting in the last decade, freeform optics has been widely recognized as an emerging optical design method for LED lighting, and it has increasing applications in most fields of LED lighting, such as ASLP, LED indoor lighting, LED road lighting, LED backlighting for LCD displays, LED automotive headlamps, LED pico-projectors, high-SCU LED lighting, and so on. Therefore, freeform optics has become the main trend of nonimaging optics design for LED lighting.

In this book, after reviewing existing major freeform optics algorithms in Chapter 2, a series of basic freeform optics algorithms and design methods specialized for LED packaging and applications will be introduced in detail in Chapter 3, such as circularly symmetrical, noncircularly symmetrical, point source, extended source, and array illumination. Following chapters will apply these algorithms in specific LED packaging and applications, including ASLP in Chapter 4, indoor lighting in Chapter 5, road lighting in Chapter 6, backlighting for large-scale LCD displays in Chapter 7, automotive headlamps in Chapter 8, emerging LED applications in Chapter 9, and high SCU in Chapter 10. Not only detailed freeform optical design methods but also many practical design cases will be presented in these chapters, so that readers can have a complete understanding of the freeform optics for LED lighting.

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