光学学报

基于表面微结构的超薄背光模组透镜设计

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摘要 根据全反射原理设计了一款基于表面微结构的超薄透镜，由自由曲面将光源出射的光线进行准直，随后利用微米级表面微结构将准直光线反射到底部，再配合底部的反射膜将光线进行二次反射，从而能够在较小的混光距离（OD）下有效增大光斑尺寸。利用边缘光线原理，改善了扩展光源下光线经自由曲面后准直性劣化问题。仿真结果表明，该透镜应用于超薄背光模组时，能够在OD为3 mm、距离-高度比（DHR）为15 mm的3×3阵列下获得82%的均匀性，相比传统双自由曲面透镜均匀性提升40.7%。该透镜设计方法简单，避免了双自由曲面透镜尺寸较小时加工误差的影响，无需后期大量复杂的优化工作，具有较大的实际应用价值。

关键词 光学设计；超薄背光源；边缘光线理论；全反射；微结构

中图分类号 TN141.9　　**文献标志码** A　　**DOI:** 10.3788/AOS221722

1 引　言

液晶显示已经成为主流的平板显示技术。由于液晶本身不发光，需要背光提供照明光线[1-4]。背光模组的亮度、色度、体积在很大程度决定了最终显示器的性能。显示产品薄型化已经成为流行趋势，这就要求液晶显示背光模组的厚度最大程度地减小。

发光二极管（LED）背光模组通常分为直下式和侧入式。侧入式背光通过导光板将侧边LED发出的点光源转换为从正面射出的面光源。直下式背光通过扩散板将底部LED发出的光均匀分散后从正面射出，可实现区域调光。直下式背光模组包含若干个阵列排布的LED光源，具有亮度高、能量利用率高、均匀性好、结构简单等优点。为降低生产成本，直下式背光模组中LED颗数越来越少，间距越来越大，需要的混光距离（OD）也随之增大，导致背光模组的厚度也随之增加。自由曲面透镜可以减小混光距离，进而大幅减小背光模组的厚度。

针对自由曲面透镜的设计方法主要包括微分方程法[5-6]、光源-目标面能量映射法[7-10]、同步多曲面法[11-12]和反馈优化设计法[13-16]。Wu等[17]为解决扩展光源下照度均匀度的问题，采用光源-目标面能量映射法设计了自由曲面透镜，照度均匀度可达到90%。曾翌等[18]为解决高距离-高度比（DHR）下照度均匀分布问题，采用了能量映射法和互补反馈校正优化法设计了DHR为3的自由曲面透镜，照度均匀度可达到87.05%。赵欢等[19]采用了几何法构建双自由曲面透镜，实现了准直照明，均匀度达到74.19%。但在OD很小的情况下，现有方法设计出的双自由曲面透镜的尺寸相对较小，且自由曲面曲率较大，以至于加工误差影响较大，并且基于点源设计的透镜在扩展光源下的匀光效果严重变差。

本文针对超薄背光模组，提出一种基于表面微结构的透镜设计方法。不同于传统的双自由曲面的透镜采用曲率较大的自由曲面将光线进行较大角度折射的原理，该透镜先将光线准直，然后通过微结构进行反射，设计出的曲面曲率较小，避免了透镜尺寸较小对加工误差的影响。

2 现有双自由曲面透镜分析

本文先采用光源-目标面能量映射法[18]设计了一款双自由曲面透镜，以便进行比较。设计时OD为3 mm、LED水平方向间距$\Delta_{\text{pitch},x}=15$ mm，垂直方向间距$\Delta_{\text{pitch},y}=15$ mm。LED芯片出射的光线经过透镜调控后，在目标面产生的光斑至少要能完全覆盖LED阵列间距，光斑半径为R，可表示为

$$R \geqslant \frac{1}{2}\sqrt{\Delta_{\text{pitch},x}^{2}+\Delta_{\text{pitch},y}^{2}}, \qquad (1)$$

收稿日期：2022-09-20；**修回日期**：2022-11-06；**录用日期**：2022-11-22；**网络首发日期**：2023-01-04

基金项目：安徽省科技重大专项(202203a05020028)

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计算得 $R\geqslant 10.6$ mm，本文取 $R=20.0$ mm。设计得到的透镜高度为1.8 mm，直径为6.26 mm，如图1(a)所示。图1(b)～(d)分别为透镜在点光源下、扩展光源下和扩展光源阵列下的照度分布仿真结果。可以看出：在点光源下仿真时，照度分布均匀，光斑 $R=20$ mm。点光源变为扩展光源时，光斑有所缩小，照度均匀性变差；在扩展光源阵列下仿真时，从结果中可以看到明显的规则排布的圆斑，后期需要大量的优化工作以使其均匀性满足要求，过程繁琐复杂。

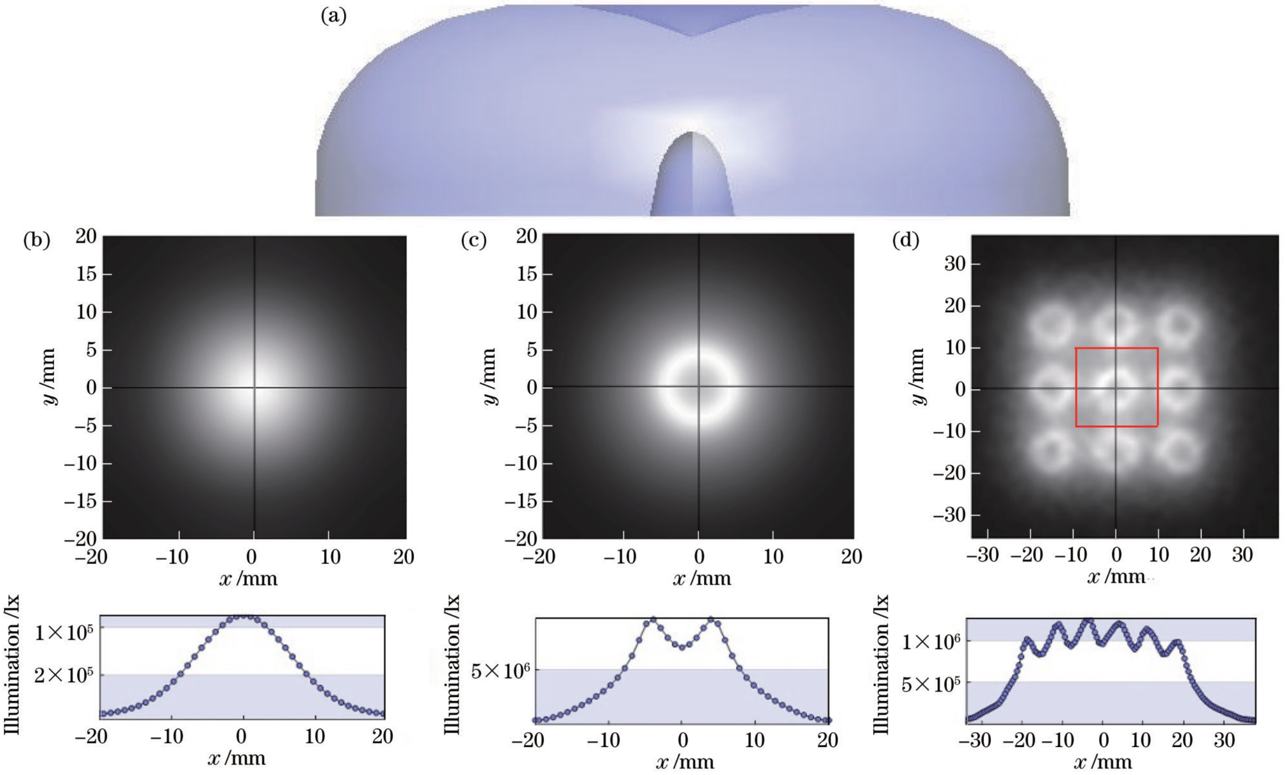

图1　双自由曲面模型及其在不同光源下的照度分布仿真结果。(a)双自由曲面模型；双自由曲面模型在(b)点光源、(c)扩展光源、(d)扩展光源阵列下的照度分布仿真结果

Fig. 1　Double free-form surface lens model and illuminance distributions simulated under different light sources. (a) Double free-form surface lens model; simulated illuminance distributions for (b) point light source, (c) extended light source, and (d) extended light source array

3　基于表面微结构的透镜设计

3.1　基于表面微结构的透镜结构

从上面的设计可以看出，采用光源-目标面能量映射法对光线直接进行扩散，在点光源转变为扩展光源后，光斑不能直接覆盖LED间距，需要后期大量的优化工作才能在阵列下得到理想的效果。此外，采用上述方法设计的透镜，整体尺寸较小，内曲面高度只有0.91 mm，且曲率较大，加工误差影响较大，存在一定的加工难度。本文借鉴全内反射(TIR)透镜结构[20]，提出一种基于表面微结构的透镜设计方法，透镜结构如图2所示，包括自由曲面 S_1、S_2、S_3 以及微结构M。首

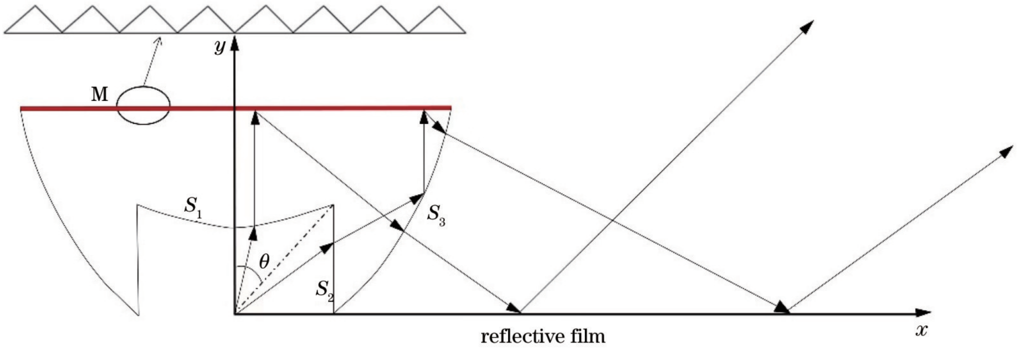

图2　透镜设计原理图

Fig. 2　Schematic diagram of lens design

先对光线进行准直，然后通过微结构进行全反射，从而增大光斑尺寸，进而在较小的OD条件下能够设计出具有较大DHR的透镜。

本设计考虑了两部分光线的角度范围：从光源出射的角度为0～θ的光线经S_1调制后准直出射到表面微结构M上，由M全反射到底部反射膜，最后由反射膜反射到目标接收面。从光源出射的角度为θ～90°的光线经S_2折射到全反射面S_3后准直出射，然后由表面微结构M全反射到底部反射膜，并由反射膜反射到目标接收面。

3.2 基于边缘光线理论的准直自由曲面设计

本文采用微米级表面微结构，将准直后的光线进行全反射以扩大光斑，因此，微结构的全反射效果严重依赖于自由曲面对光线的准直效果。然而，依据点光源设计的传统TIR透镜，其准直效果在扩展光源下并不理想，以至于透镜在扩展光源下的中心亮度过高。图3(a)、(b)分别为传统TIR透镜在点光源与扩展光源下的照度分布图，可以看出：在点光源下照度分布均匀，光斑半径为20 mm；但在扩展光源下光斑半径只有15 mm，且照度分布不均匀。所以本文提出基于边缘光线理论的自由曲面设计方法，该方法在扩展光源的基础上进行设计，规避了点光源转变为扩展光源时繁琐的优化步骤，简化了设计流程。以S_1为例，设计如图4所示。

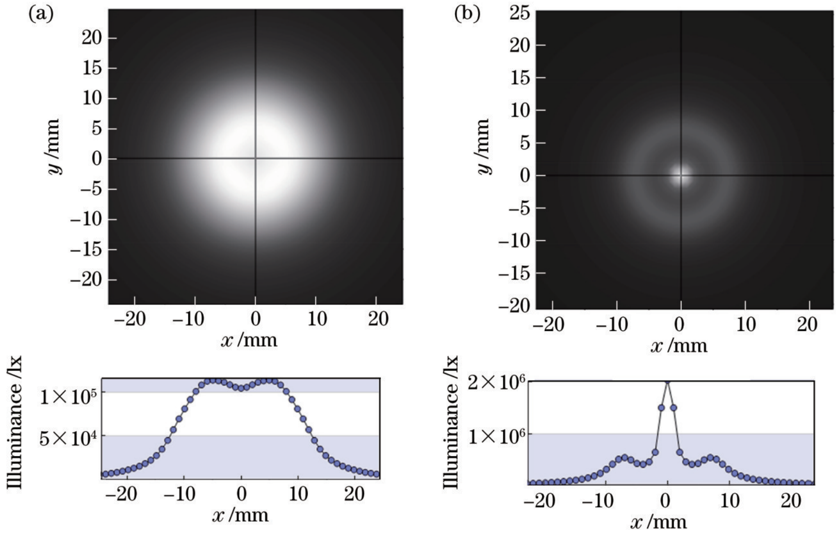

图3 传统TIR透镜的仿真照度分布图。(a)点光源；(b)扩展光源

Fig. 3 Simulated illumination distributions of traditional TIR lens. (a) Point light source; (b) extended light source

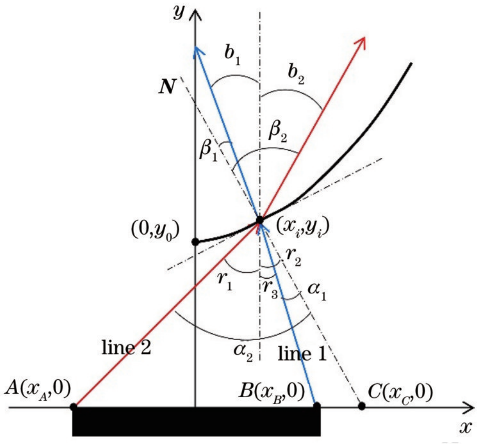

图4 曲面S_1的设计原理图

Fig. 4 Design schematic diagram of surface S_1

图4中，$(0, y_0)$为曲面初始点，假设(x_i, y_i)为曲面上一点，line 1及line 2为扩展光源的2条边缘光线，b_1、b_2分别为经自由曲面调控后的2条边缘光线与垂直方向的夹角，β_1、β_2分别为line 1与line 2的出射光线与法线的夹角，α_1、α_2分别为line 1与line 2的入射光线与法线的夹角，r_1为line 2与垂直方向的夹角，r_2为法线与垂直方向的夹角，r_3为line 1与垂直方向的夹角，$A(x_A, 0)$、$B(x_B, 0)$分别为line 2与line 1在x轴上的交点，$C(x_C, 0)$为法线在x轴上的交点，$\boldsymbol{N}$为法向量。

根据几何光学原理，可以得到下列方程组：

$$\left\{\begin{aligned}
r_1 &= \arctan\frac{x_i - x_A}{y_i}\\
r_2 &= \arctan\frac{x_C - x_i}{y_i}\\
r_3 &= \arctan\frac{x_B - x_i}{y_i}\\
\alpha_1 &= r_2 - r_3,\\
\alpha_2 &= r_1 + r_2\\
\beta_1 &= \arcsin\left(\frac{1}{n}\sin\alpha_1\right)\\
\beta_2 &= \arcsin\left(\frac{1}{n}\sin\alpha_2\right)
\end{aligned}\right., \tag{2}$$

式中：n为透镜材质的折射率。

由式(2)可以分别得出line 1与line 2的出射角度

β_1、β_2，为了使出射光线趋于准直，需要限制出射角度。本文取b_1、b_2作为限制条件对出射光线进行限制：

$$\begin{cases} b_1=|\beta_1-r_2| \\ b_2=|\beta_2-r_2|\text{。} \end{cases} \tag{3}$$

结合式(2)、(3)计算出当b_1+b_2的和取得最小时的(x_i,y_i)值，由此迭代计算得到曲面S_1。曲面S_2、S_3的设计同理可得。经过设计的曲面S_1、S_2、S_3需满足设计条件，将从扩展光源发出的光线进行准直。

3.3　基于全反射的表面微结构设计

为发散经自由曲面准直的光线以达到增大光斑半径的效果，本文利用表面微结构来反射从曲面S_1、S_2、S_3出射的准直光线。根据光线全反射条件，光线由光密介质入射到光疏介质时，如果入射角大于临界角，则发生全反射。临界角的计算式为

$$\gamma \geqslant \arcsin\frac{n_2}{n_1}, \tag{4}$$

式中：n_1为光密介质的折射率；n_2为光疏介质的折射率。本设计中透镜材质的折射率$n_1=1.495$，空气折射率$n_2=1.000$，故计算得$\gamma \geqslant 42°$。

本文基于上述理论设计的用于全反射光线的表面微结构为周期性三角形，高度为10 μm。设计原理如图5所示。

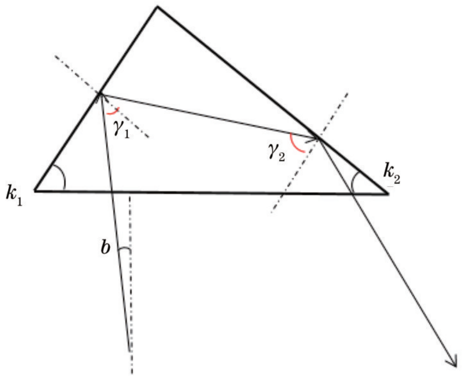

图5　微结构设计图

Fig. 5　Microstructure design diagram

由图5可得：

$$\begin{cases} k_1=b+\gamma_1 \\ k_2=180°-k_1-\gamma_1-\gamma_2 \end{cases}, \tag{5}$$

k_1、k_2决定了微结构的反射效果，其大小由入射光线与垂直方向的夹角b所决定。夹角b越小，微结构的反射效果越好。

4　透镜的仿真及优化

本文设置$b_1=20°$、$b_2=8°$、$y_0=0.5$ mm。将由式(2)、(3)所得曲面S_1导入LightTools中进行仿真，光源为0.7 mm×0.7 mm的扩展光源。

如图6所示，半照度峰值处光斑半径为1.1 mm，出射的大角度光线较多，光线分布较散，准直效果不理想，其主要原因是：扩展光源左边缘光线未能出射到曲面S_1的后半段，导致曲面S_1对line 2没有调节作用。于是，本文对上面的设计方法进行优化，由于该透镜结构为对称结构，一半扩展光源发出的多数光线出射在同侧曲面上，所以对扩展光源进行对半设计，得到优化曲线S_1-1，设计如图7所示。

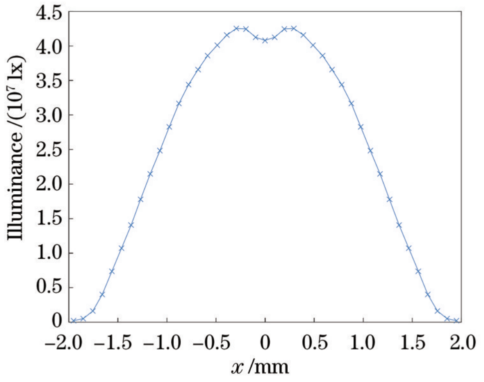

图6　曲面S_1的扩展光源照度曲线图

Fig. 6　Illuminance curve of surface S_1 for extended light source

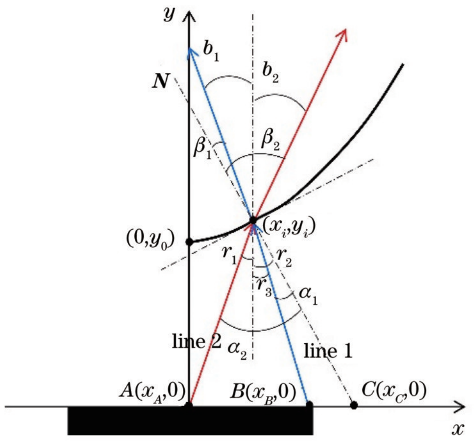

图7　曲面S_1-1的优化设计图

Fig. 7　Schematic diagram of optimization design of surface S_1-1

按照图7所示流程进行设计，得到曲面S_1-1。将S_1-1导入LightTools中用扩展光源进行仿真。

如图8所示，优化曲面S_1-1的半照度峰值处的光斑半径为0.68 mm，相较于曲面S_1，经曲面S_1-1出射的大角度光线大部分都收敛到中心区域，对扩散的光线有收缩作用，说明将扩展光源进行对半设计具有一定成效。于是本设计继续对设计参数b_1、b_2与y_0进行优化调整，以$b_1=20°$、$b_2=8°$、$y_0=0.5$ mm为初始值，以0.05 mm为步进值，对y_0进行优化，得到最优解$y_0=0.7$ mm。以1°为步进值对b_1、b_2进行相同的优化步骤，得到$b_1=5°$、$b_2=15°$。最终得到曲面S_1-2的仿真效果如图9、10所示。

由图9、10可以看出，经优化的曲面S_1-2出射的大角度光线减少，光线出射集中在中心区域，准直效果明

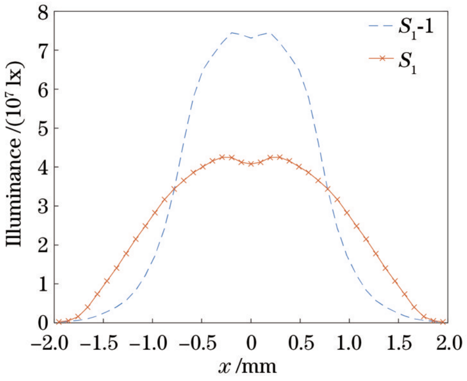

图 8 曲面 S_1 和优化曲面 S_1-1 的扩展光源照度曲线图

Fig. 8 Illuminance curves of surface S_1 and optimized surface S_1-1 for extended light source

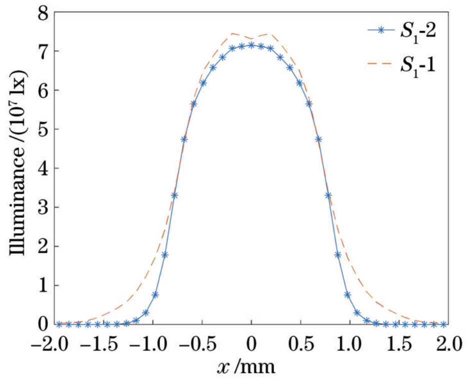

图 9 曲面 S_1-1 和二次优化曲面 S_1-2 的扩展光源照度曲线图

Fig. 9 Illuminance curves of surface S_1-1 and quadratic optimized surface S_1-2 for extended light source

显。同理，经优化设计可得到曲面 S_2-2、S_3-2。最终得到入射光线与垂直方向的夹角 $b=11^\circ$。为使光线发生全反射，取 $\gamma_1=43^\circ$，由式(5)得到 $k_1=53^\circ$。为使光线发生全反射后的角度更大，取 $\gamma_2=45^\circ$，得到 $k_2=40^\circ$。

将微结构与曲面 S_1-2、S_2-2、S_3-2 相结合，得到透镜高为 1.5 mm，直径为 3.12 mm。在 LightTools 中用尺寸为 0.7 mm×0.7 mm 的扩展光源进行单颗以及阵列仿真，得到照度仿真图如图 11 所示，单颗透镜在扩展光源下仿真的光斑半径为 25 mm，且光斑均匀，使用扩展光源阵列时光斑可以直接覆盖 LED 间距。为了定量地评估阵列情况下的照度均匀性，选取图 11(b)所示的阵列仿真照度图中虚线方框区域内的最小照度值 $I_{\min}$ 及最大照度值 $I_{\max}$ 进行计算，均匀性 μ 可表示为

$$\mu=\frac{I_{\min}}{I_{\max}}\times 100\%, \tag{6}$$

得到扩展光源透镜在阵列情况下的目标面照度均匀性为 82%。为了更好地与双自由曲面透镜进行对比，本文对传统双自由曲面透镜进行了仿真，如图 12 所示，点光源设计的双自由曲面透镜在扩展光源下，在 ±5 mm 的位置处的照度出现较大峰值，这需要后期大量的优化工作进行调整。相较而言，本文设计的基于表面微结构的超薄透镜在扩展光源下可以实现均匀的照度分布。

均匀性比较选取同样的区域下进行，由式(6)计算得，采取图 1(d)所示的阵列时的照度均匀性仅为 41.3%。

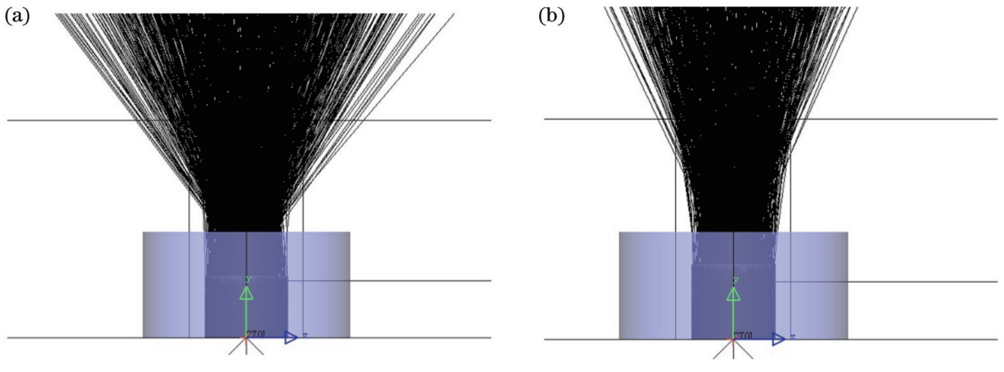

图 10 扩展光源光线图。(a)曲面 S_1-1；(b)二次优化曲面 S_1-2

Fig. 10 Extended light ray graphs. (a) Surface S_1-1; (b) quadratic optimized surface S_1-2

5 结论

提出一种基于表面微结构的超薄透镜设计方法。该设计方法利用边缘光线原理，有效改善了扩展光源下光线经自由曲面后准直性劣化问题。对比双自由曲面透镜，发现本文设计减少了点光源转变为扩展光源后大量的后期优化工作，通过微米级表面微结构反射由自由曲面准直出射的光线，反射的光线被底部的反射膜再次反射，能够在较小的 OD 下增大光斑尺寸。仿真结果表明，该透镜应用于超薄背光模组时，光线扩散效果得到显著改善，能够在 OD 为 3 mm、DHR 为 15 mm 的 3×3 阵列下获得 82% 的均匀性，相比传统双自由曲面透镜均匀性提升 40.7%，且透镜设计方法简单，在小尺寸基础上降低曲面曲率，避免了透镜尺寸较小对加工误差的影响。本文设计无需后期大量复杂的优化工作，具有较大的实际应用价值。

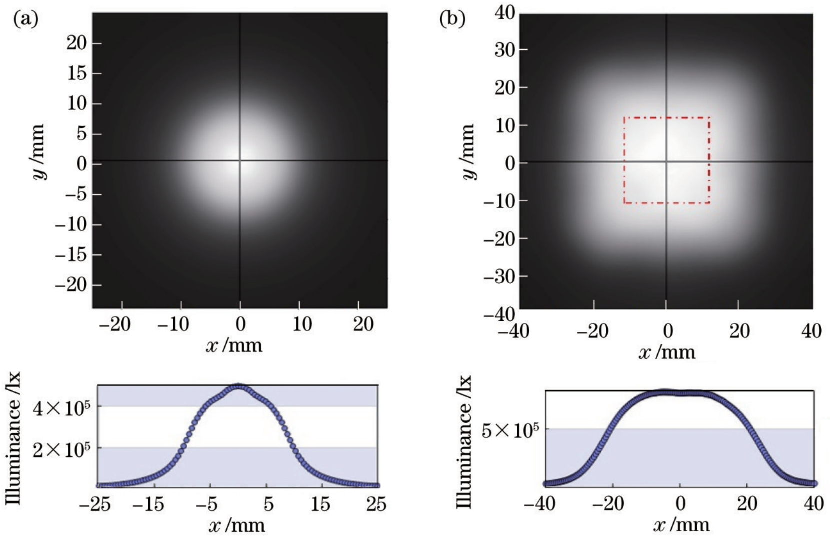

图11 透镜仿真照度分布图。(a)扩展光源；(b)扩展光源阵列

Fig. 11 Simulated illuminance diagrams of lens. (a) Extended light source; (b) extended light source array

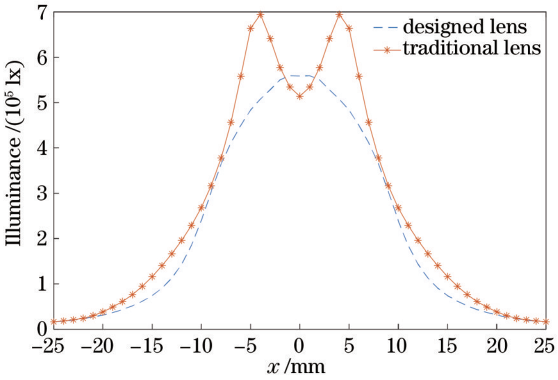

图12 传统双自由曲面透镜与本文设计透镜的扩展光源照度曲线对比图

Fig. 12 Illuminance curves based on extended light sources with traditional double free-form surface lens and lens designed in this paper

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Surface Microstructure-Based Ultra-Thin Backlight Unit Lens Design

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Abstract

Objective Because liquid crystal itself does not emit light, a backlight unit (BLU) is needed to provide illumination rays. The brightness and volume of a BLU largely determine the performance of a display. Ultra-thinness has become a popular trend, which requires a light-emitting diode (LED) BLU to minimize its thickness as soon as possible. The direct-lit BLU has the advantages of high brightness, high energy utilization rate, and good uniformity. In order to reduce the production cost, the number of LEDs in the direct-lit module is decreasing, and the distance between LEDs is increasing, which makes the optical distance (OD) larger. Free-form lenses have been widely used in direct-lit BLUs to reduce the thickness and increase the distance-height ratio (DHR). However, when the OD is quite small, the size of the designed lens is relatively small, which results in a large processing error. Furthermore, the illuminance uniformity will be reduced when the lens designed based on the point source method is used for the extended light source. A lot of complicated optimizations are needed to improve uniformity. Therefore, an ultra-thin lens based on the surface microstructure is designed in this paper. The lens first collimates the rays emitting from an LED and then reflects the rays by the microstructures, which can increase the size of the illumination spot during the limited OD. The curvature of the designed surface is small, which can help avoid the influence of processing errors.

Methods In this paper, a lens design method based on the surface microstructures is proposed for an ultra-thin BLU that consists of an array of LEDs with a pitch of $\Delta_{\text{pitch},x} \times \Delta_{\text{pitch},y}$ ($\Delta_{\text{pitch},x}$ is pitch of x direction, and $\Delta_{\text{pitch},y}$ is pitch of y direction). This design is different from the traditional double free-form surface lens which uses the free-form surface with a large curvature to refract the light at a larger angle. In this paper, the free-form surface is used to collimate the rays from the light source, and then the collimated rays are reflected to the bottom by the surface microstructure. After that, the rays are reflected again by the reflection film at the bottom so that the spot size can be effectively increased under the small OD. In addition, the collimation effect of a traditional total internal reflection (TIR) lens designed based on a point light source is not ideal under an extended light source. Therefore, the proposed method uses the edge ray principle to improve the collimation of the rays passing through the free-form surface under the extended light source. It requires no complicated optimization when the point light source is replaced by the extended light source.

Results and Discussions The design is carried out in a BLU with a mini-LED number of 3×3, an array pitch of 15 mm×15 mm, and an OD of 3 mm. Based on Snell's law, the paper firstly designs three free-form surfaces to collimate the ray emitted by the light source and then designs surface microstructures to reflect the collimated rays to the bottom (Fig. 2). In addition, based on the edge ray principle, the paper optimizes the free-form surfaces so that it can improve the collimation of the rays when the light sources are changed to the extended ones (Fig. 10). The simulation model is built in LightTools. The simulation results show that the uniformity can reach 82% for a 3×3 LED array with an OD of 3 mm and a DHR of 15 mm. Compared with that of the traditional double free-form surface lens, the uniformity is improved by 40.7%.

Conclusions Free-form surface lenses have been widely used in direct-lit BLUs to reduce the thickness and increase the DHR. However, when the OD is small, the size of the designed lens is relatively small, which results in a large processing error. In addition, the illuminance uniformity will be reduced when the lens based on the point source method is used to form the extended light source. In this paper, an ultra-thin lens based on the surface microstructure is designed according to the TIR principle. The free-form surfaces are used to collimate the rays from the light sources. Then the collimated rays are reflected to the bottom by the microstructures. The rays are reflected once more by the reflection film. Therefore, the spot size can be effectively increased under the small OD. In addition, the edge ray principle is used to improve the collimation of the rays passing through the free-form surface under extended light sources. With no larger curvature, the designed lens can avoid the influence of processing error and achieve satisfying illumination. The proposed method does not need a lot of complicated optimization work, which presents high practical application value.

Key words optical design; ultra-thin backlight; edge ray theory; total reflection; microstructure