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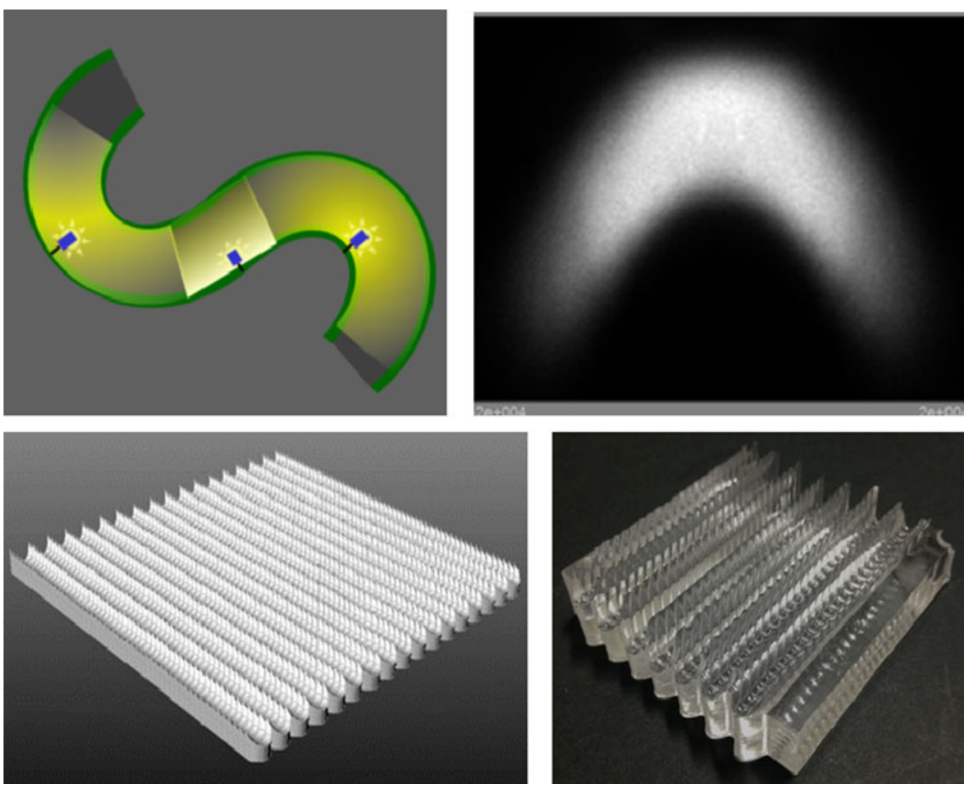

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Abstract: Street lighting, which is one of the main players in energy waste and light pollution at night, still faces the challenge of efficient lighting of roadways with curved and twisted shapes. To meet this challenge, we propose an effective and efficient adaptive light-emitting diode (LED) luminaire. This LED lamp delivers a roadway-shape light pattern, which maximizes illumination performance. The light is efficiently and homogeneously directed only where is needed; which reduces glare, and improves both the eye comfort and the visual discrimination ability of car drivers and pedestrians. The proposed luminaire is very practical in that it only requires to replace the cover plate, which is a special microlens array sheet, to produce different shape light patterns. The adaptive mechanism is simple and effective: LED light is first collimated and then efficiently distributed on a freeform roadway by the special microlens sheet. We present an extensive analysis of the lighting adaptability of the proposed luminaire by Monte Carlo ray tracing. In particular, we studied the effect of the main microlens structural parameters in the shape and size of the delivered illumination distribution on the roadway. We present a design example, a prototype construction, and an experimental confirmation on a scale street lighting system. Simulations and experimental results show the advantages of adaptive luminaires over the traditional nonadaptive approaches.

Index Terms: Light-emitting diodes (LEDs), nonimaging optical systems, illumination design, optical design and fabrication, illumination.

1. Introduction

The superior performance of light-emitting diode (LED) street lights is changing the way we think about city lighting [1]. LED luminaires for road lighting have the potential to deliver precise beam patterns to minimize light pollution, increase comfort and visibility, and maximize efficiency by directing light to the appropriate area. LED luminaires also have the potential of increasing illumination

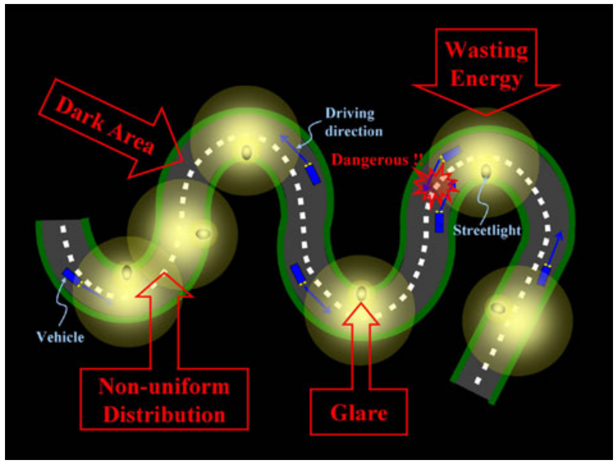

Fig. 1. Shortcomings of traditional street lighting on roads with arbitrary shape.

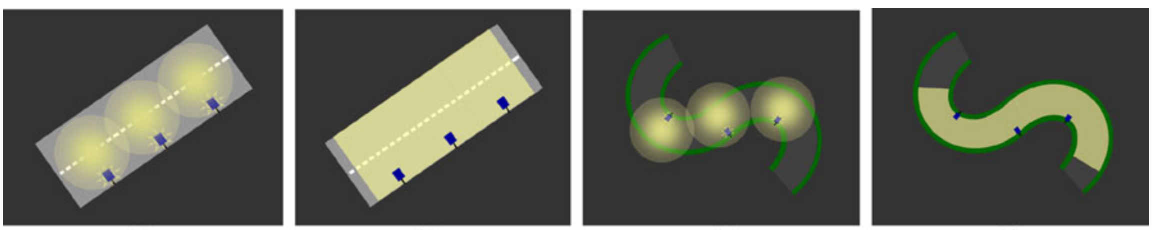

Fig. 2. (a) Light distribution of straight streets in traditional and (b) adaptive street lighting. (c) Light distribution of free-form streets in traditional and (d) adaptive street lighting.

uniformity, which, together with glare reduction, improves both the eye comfort and the visual discrimination ability of car drivers [2], [3]. This is why, over the past few years, local governments in cities across the world have been improving street lighting by investing in energy-efficient LED technologies, which may provide a unique opportunity to reduce both financial and environmental loads [1].

Old street lighting technologies, such as high-pressure sodium or mercury, emit light in all directions, and consequently the light distribution is difficult to control. These luminaires usually have defects such as glare, non-uniform light pattern, upward reflected light, light pollution, and waste of energy. Also, old lighting technologies limit both eye comfort and visual discrimination ability of car drivers and pedestrians. Such shortcomings are magnified when lighting roads of arbitrary shape, as shown in Fig. 1. In this context we introduce a new concept of adaptive street lighting. Fig. 2 shows a schematic comparison between traditional and adaptive street lighting. Fig. 2 shows how much of the light is lost out of the road, the illumination is not uniform, and the light falling outside may cause eye discomfort for drivers and pedestrians. On the other side, using adaptive LED lighting, energy is saved because it is not wasted to the sky or the sides of the street.

In this paper, we propose a novel scheme of high-performance LED luminaire for adaptive street lighting. Its light emission is able to adapt to the street shape by delivering an illumination distribution with the shape of the road, and then maximizes illumination performance by directing light only where it is needed. The luminaire delivers high light output, high beam control, and low glare in street lights. Its optics efficiently and homogeneously distributes light on a free-form street; which is a requirement for reducing glare, and improving both the eye comfort and the visual discrimination ability of car drivers. Its optics is simple and effective, which collimates and recycle LED light, and then a combination of beam shaping and light diffusion efficiently and homogeneously delivers light into an arbitrary-shape road.

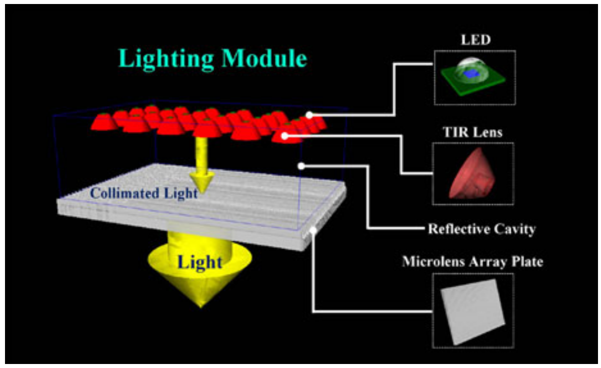

Fig. 3. Schematic diagram of an adaptive LED luminaire with microlens array.

2. Adaptive LED Luminaire

The proposed LED street luminaire consists of a module that is easy to design and fabricate, as shown in Fig. 3. Its optics is simple and effective: an array of LEDs with total internal reflection (TIR) lenses are put inside a reflective cavity, which is covered with a special microlens sheet; the reflective cavity improves the efficiency by recycling the back-reflected light; each TIR lens efficiently collimates the LED light for the microlens array; and the microlens plate combines beam shaping and light diffusion to efficiently and homogeneously deliver light into the free-form street. The microlens plate plays a key role in the whole module because it is the adaptive optical element. An LED luminaire with rectangular aperture microlenses delivers a rectangle light pattern that fits straight streets or roads. A full analysis of high-performance LED luminaires that produce rectangular light distributions was described in detail in [2], [3], and highlighted in several media [4]. Such a novel LED luminaire was capable to reduce light pollution up to 2%, whereas in the best LED-based designs on the market 10% of the energy was responsible for light pollution. Besides, for those straight roadways, many approaches can also make the lighting pattern to fit roadway shape, such as using cylindrical lens array or free-form TIR lens, which can be easily designed and fabricated [5]–[7].

For non-straight shape roads, the situation is almost different though few research solutions have been reported. A non-imaging optics for individual LEDs have been proposed to solve the problem of small curved roads like those of city parks [8], but they require several optical components that are prone to alignment issues, are not suited for large and pronounced curve roads, and are not completely adaptive. Our approach is a high-performance solution because it is adaptive, efficient, and has low sensitivity to manufacturing tolerances. The illumination distribution on the street depends on the aperture shape of every microlens unit. Then, our approach only needs to interchange one single element, which is the luminaire cover (microlens plate) to efficiently illuminate different shape roads.

3. Optical Elements of the Adaptive LED Luminaire

The LED luminaire incorporates three optical elements: TIR lenses, a reflective cavity, and a special microlens sheet. Each TIR lens collimates the LED light for correct light management; the reflective cavity improves the efficiency by recycling light that is back and side directed; and the special microlens sheet uniformly distributes light only within the street boundaries. Here we describe and model every optical element of the lighting module, and we specify the desired lighting performance.

3.1 TIR Lens and Reflecting Case

TIR lenses are attached to LEDs in order to make light rays as much as possible parallel to each other. This light collimation is necessary for optimal microlens array performance. The design and modeling of a TIR lens depends on how good the LED optical model is [9]–[15]. To build up the LED model, first an LED must be chosen, and then we selected a modern high-power type, the Cree XP-G white LED. The midfield modeling method [9] was implemented to build up the LED model, which correlates optical simulations with experimental measurements in the midfield region.

Once the LED model was implemented, we proceed to design the TIR lens [14], [15]. The designed TIR lens should have a collimating effect on LED light to enhance the performance of microlens plate, as shown in Fig. 3. The LED emission angle should be narrowed by TIR lens as much as possible. The radiation pattern of Cree XP-G LED has a emission divergence angle of $\sim$120°. For which we designed and modeled a TIR lens that narrows the divergence angle from 120° to 12°, with an optical efficiency of 87.5%. Although LED collimation is not perfect, this 12° beam divergence is useful to soften lighting, and to also illuminate a street region for pedestrian use.

A housing box is needed to support and protect LEDs from environment. In our design, the housing is also a reflecting cavity with the property of photon recycling for increasing the optical efficiency of the whole module [16]. We modeled the inner walls of the cavity as high reflective sheet, with a reflectance of 85%. The inner surfaces included four side walls and one bottom, as shown in Fig. 3. In order to balance LED-to-LED separation, volume, and weight, in our analysis, we set the cavity size as 130 mm $\times$ 100 mm $\times$ 80 mm.

3.2 Special Microlens Array

Structured microlens arrays have the beam shaping capabilities of diffractive elements plus the homogenization properties of random diffusers [17], [18]; more important, they operate efficiently without color separation under the broadband spectra of white LEDs [2], [18]. The lens structure must be small for achieving light homogenization. A key feature is that each microlens distributes the light in a large part of the illumination pattern, and then, manufacturing tolerances may be very high. Although the fabrication process may be expensive and complex; recently a high-performance, large-area, and low-cost structured microlens array was introduced [18]. Such development makes structured microlens array plates easy to fabricate and implement in real-world street lighting systems.

The microlens plate is the adaptive optical element in the LED luminaire. This element has the ability to place LED light within the road boundaries. A special microlens structure may produce a light pattern that just cover a roadway section without wasting light out of this region. In a straight roadway each microlens unit must have a parabolic profile within a rectangular shape aperture [2]. We discovered that bending the aperture shape of each microlens unit may efficiently curve the illumination pattern. Fig. 4 shows these two cases: lens units with rectangular and curved apertures. Both a 3-D view and a top view are shown. The resulting illumination pattern is also included. Microstructure in Fig. 4(d) has the same lens profile but twisted aperture, which transforms light distribution from a rectangular shape into a curved light distribution. This curved light pattern has notable attributes like low light waste, high illumination uniformity, and high light distribution efficiency.

Fig. 5 shows a 3-D view of the surface structure of both the complete plate and a single lens unit with bended aperture. Fig. 5(a) shows the microlens array plate. Fig. 5(b) shows an enlarged view of a single micro-lens unit, which indicates the main dimensions of a single lens: length L, width W, and height H. These parameters off-center shift are used in next section for the optical analysis. These parameters are carefully adjusted to achieve high-efficiency and adaptability of illumination to the road shape.

4. Optimization of Lens Array Design

The purpose of this section is to analyze the effect of key parameters of the lens array structure in the optical performance of the LED luminaire by using Monte Carlo ray tracing. The analysis focuses on the illumination distribution and the optical efficiency. The ray tracing considers a reflecting cavity

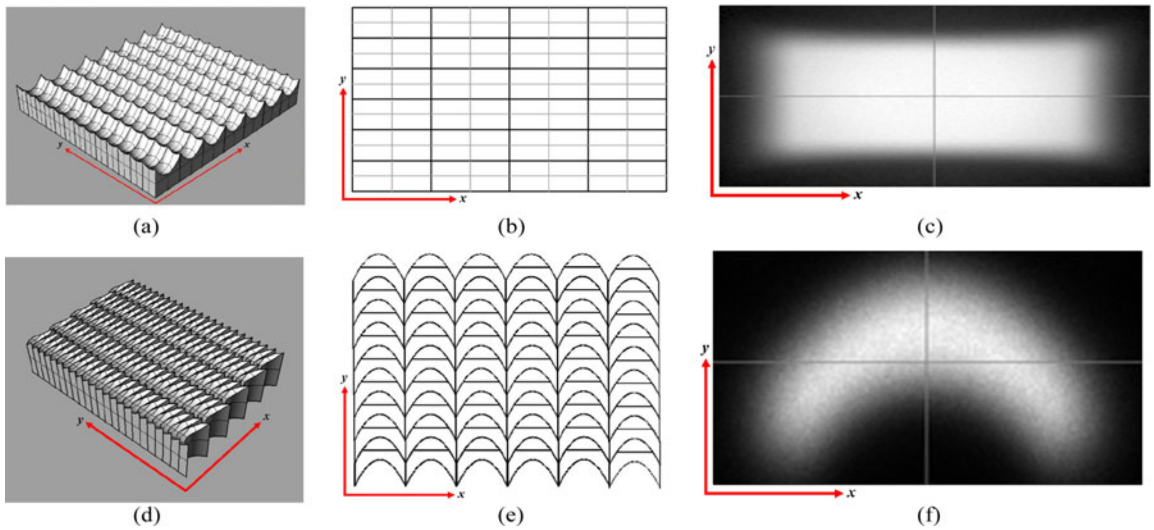

Fig. 4. (a) Three-dimensional view, (b) the top view, and (c) the produced light distribution on the street of microlens array plate with rectangular aperture. (d) Three-dimensional view, (e) the top view, and (f) the produced light distribution on the street of microlens array plate with bended aperture.

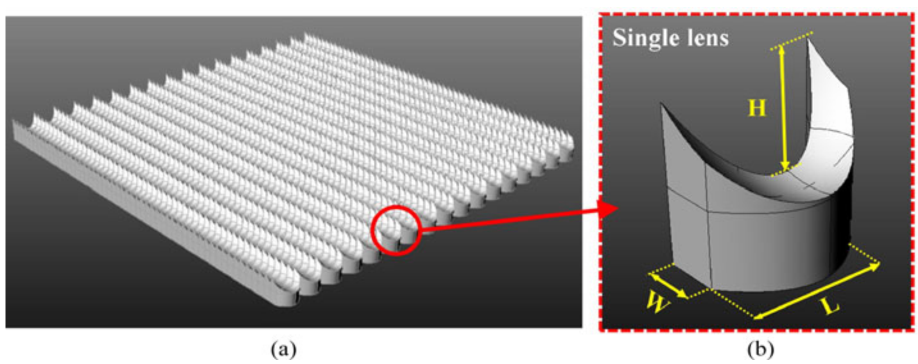

Fig. 5. (a) Adaptive microlens array plate and (b) a zoom of its lens structure, which shows parameters H, W, and L.

that contains an array of 18 pcs 5 W Cree XP-G LEDs with TIR lenses. A total of 54 million rays were traced to simulate the optical performance for each run, 3 million rays per LED. We consider an aperture bending of 0.1 mm. Each of the following LED luminaries under analysis is considered to be mounted at a height of 12 m from the roadway surface. All the following illumination distributions are the illuminance profile at the roadway surface.

4.1 Effect of Micro Lens Depth

Let us start with the analysis of the effect of microlens depth H. As we said above, the desired effect is to control the shape and size of the illumination distribution on the street or roadway. Also, we should look for high optical efficiency. Fig. 6(a) to (j) show the illumination pattern produced by our LED luminaire for different values of depth H. All images of Fig. 6(a) to (j) represent a top view of the street of 44 m $\times$ 24 m. We varied lens depth from 0.5 mm to 5 mm to analyze its effect on illumination distribution. The luminaire achieves a curved light distribution whose shape is barely affected by parameter H, but the size of illumination pattern considerably increases with this lens parameter. It is interesting to note that light pattern size increases nearly linearly with H. On the other side, the optical efficiency is high for small H values and slowly reduces by increasing H.

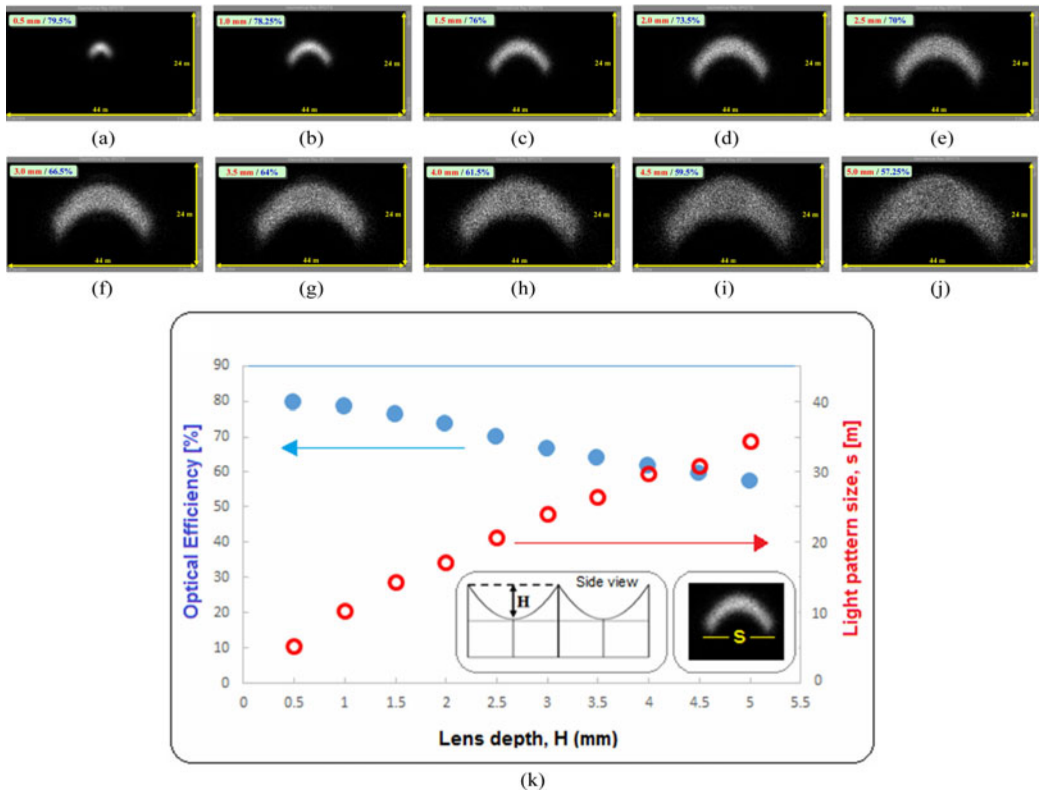

Fig. 6. Effect of microlens depth on street illumination spatial distribution. (a)–(j) shows the light pattern produced by a LED luminaire for different microlens depths H. Inset in (a)–(j) shows the note of lens depth H / optical efficiency. (k) Trade-off between luminaire optical efficiency and the size of the illumination pattern at the street. Microlens parameters are L = 2 mm and W = 0.4 mm. Inset in (k) shows both lens side view and size s.

Fig. 6(k) shows a corresponding relation with microlens depth, light pattern size, and optical efficiency. The light pattern size decreases by reducing lens depth because of the surface become more flat, the refractive power of lens surface decline, and then light rays are less deviated by the micro lens array.

4.2 Effect of Micro Lens Width

Now let us analyze of the effect of microlens width W. Fig. 7 shows the illumination distributions from the LED luminaire on the street for different values of lens width. All images of Fig. 7 represent a top view of street of 17 m $\times$ 13 m size. We varied microlens width from 0.2 mm to 1.8 mm to analyze its effect in lighting. The effect is a change of shape of the illumination distribution on the street or roadway, which follows the aperture shape of the microlens unit. See the similitude of light pattern shape and the inset lens top view in diagonal images of Fig. 7. The luminaire achieves a curved light distribution whose shape is narrowed if microlens apertures are narrowed by increasing W. We also note that light pattern size slightly decreases with W. On the other side, the optical efficiency is high and barely affected by width W.

4.3 Effect of Micro Lens Length

The next parameter is microlens length L, let us analyze its effect in the light distribution. Fig. 8 shows the illumination distributions on the street for different values of L. All images of Fig. 8 represent a street top view of 30 m $\times$ 24 m. We varied lens length from 4 mm to 1.5 mm. The

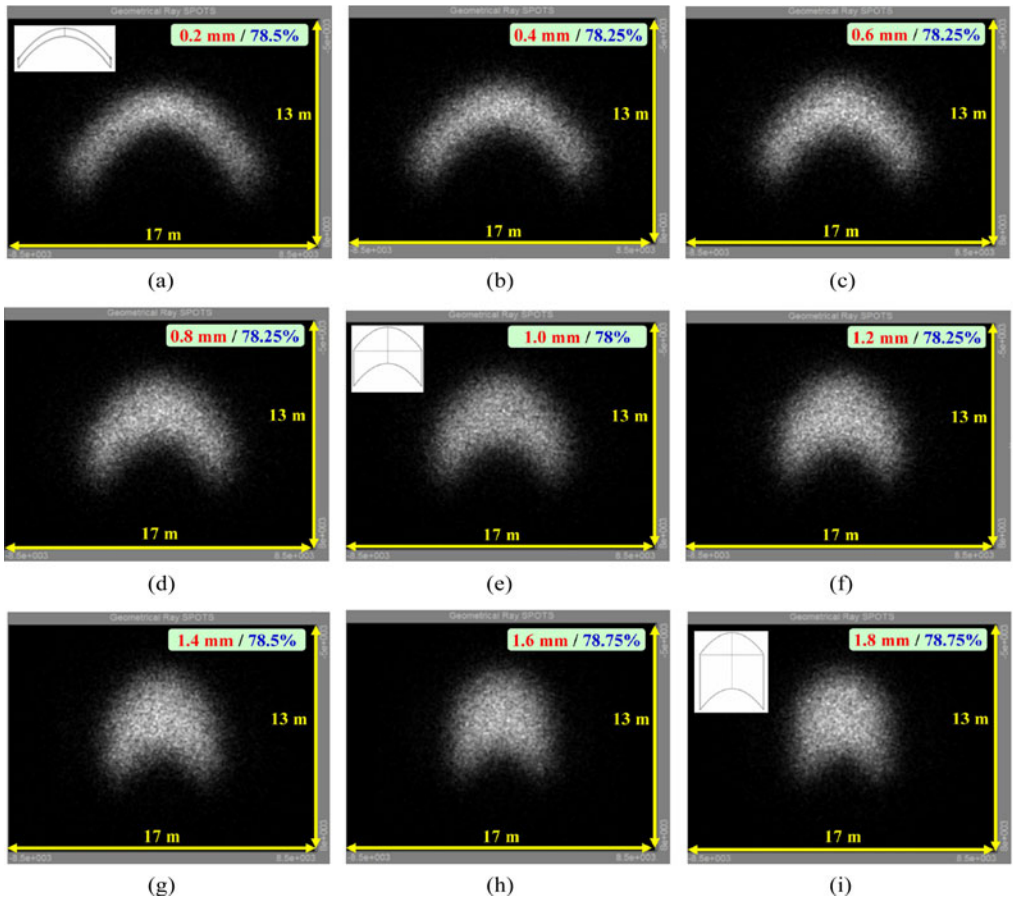

Fig. 7. Effect of microlens width on street illumination spatial distribution. Images show the light pattern produced by a LED luminaire for different microlens widths W. Insets in (a)–(i) show the note of lens width W / optical efficiency. Microlens parameters are L = 2 mm and H = 1 mm. Insets in diagonal images show a top view of microlens.

effect is a change of both shape and size of the illumination distribution, which somehow follows the contour shape of the microlens unit. See the similitude of light pattern shape and the inset microlens scheme in Fig. 8(a) and (f). The luminaire achieves a curved light distribution whose shape is narrowed and its size reduced if microlens length reduces. On the other side, the optical efficiency increased by reducing length parameter L.

The light pattern size decreases with reducing L because the microlens profile becomes more flat. Light rays cross the lens through its central section that is less curved, and then light rays are less deviated by the micro lens array. This is also the reason why optical efficiency increases with reducing L.

4.4 Effect of Off-Center Micro Lens Profile

Finally we analyze the effect of lens off-center shift on the light distribution. In the preceding three cases, the curvature center of the microlens profile was kept in the same position than in the rectangular aperture microlens. This center is indicated by two crossed lines in Fig. 5, and in the insets at Figs. 7 and 8. The off-center shift is illustrated in Fig. 9(a), which shows a top view of both rectangular and a bended microlens apertures. Fig. 9(b) and (c) show the illumination distributions on the street from rectangular shaped microlenses with off-center shift in the y and x-directions respectively. The high contrast of these two illumination patterns is because the microlens array is

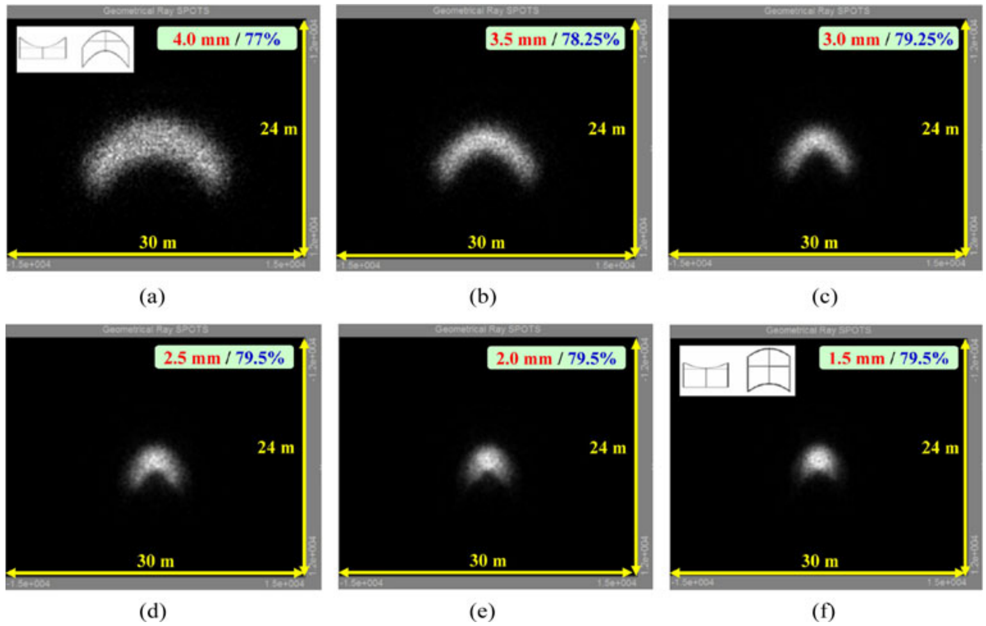

Fig. 8. Effect of microlens length on street illumination spatial distribution. Images show the light pattern produced by a LED luminaire for different microlens lengths L. Insets in (a)–(f) show the note of lens length L / optical efficiency. Microlens parameters are W = 2 mm and H = 1 mm. Insets show a top view of microlens.

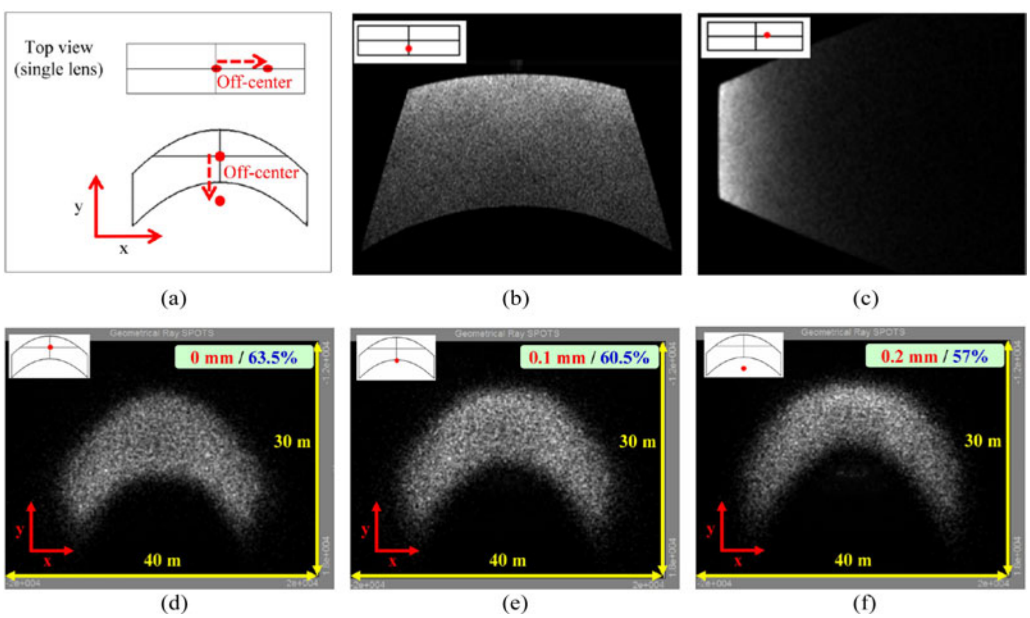

Fig. 9. Effect of off-center the microlens profile on street illumination distribution. (a) Lens top views that illustrate the off-center concept. (b) Light pattern produced by rectangular aperture microlenses with off-center shift in the y direction and (c) the x direction. (d) Illumination distribution using twisted microlenses without the effect of off-center shift. (e) Illumination distribution using bended microlenses with the off-center shift of 0.1 mm and (f) 0.2 mm in the y direction. Microlens parameters are L = 0.56 mm, W = 0.2 mm, and H = 1.5 mm. Insets show a top view of microlens unit and the note of off-center shift distance / optical efficiency.

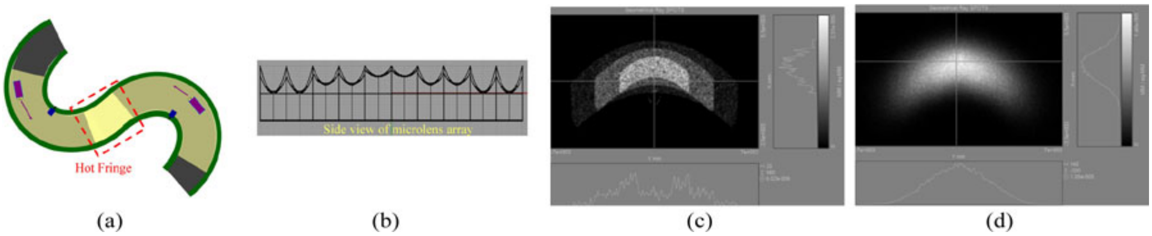

Fig. 10. Adaptive street lighting design by illumination redistribution. (a) Problem of hot fringe in the proximity of two luminaries. (b) Non-homogenous distribution of lens depth H in a microlens array. (c) Illumination distribution due to different illuminated sections of microlens array with varying H. (d) Ilumination distribution produced by a LED luminaire with the plate shown in (b).

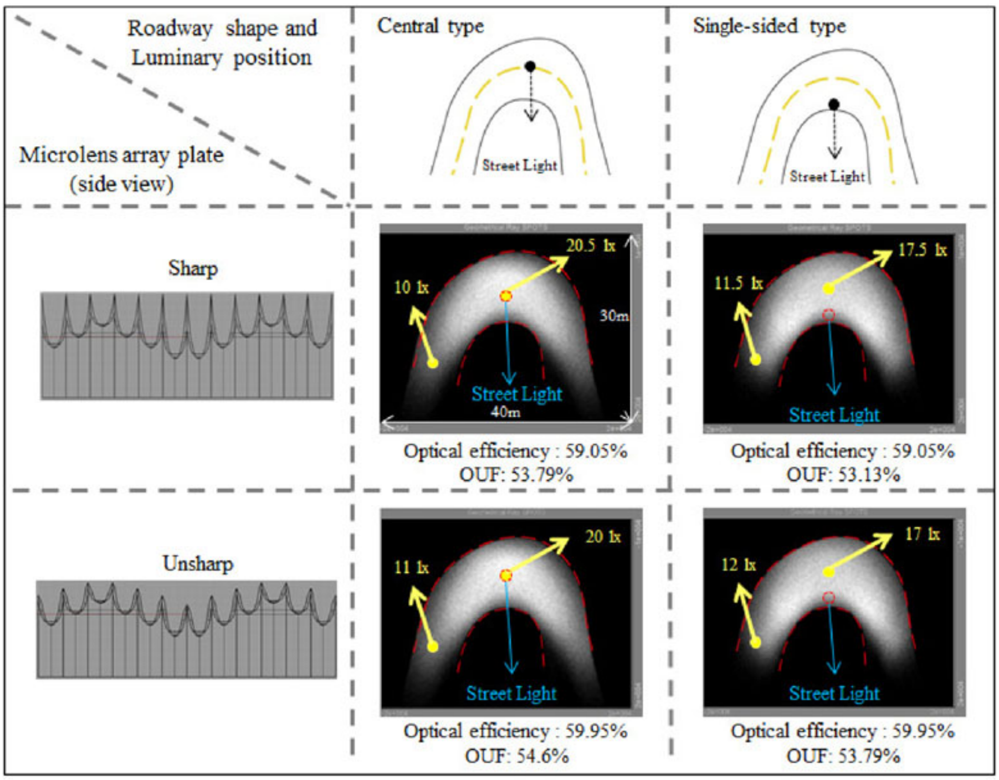

Fig. 11. Adaptive LED lighting for a sharp curve shape roadway. It shows the optical efficiency and OUF for two different pole positions and microlens plates.

illuminated by a perfect collimated beam of light. Fig. 9(d) to (f) shows an illumination pattern using bended microlens arrays, all for an area of 40 m $\times$ 30 m. Fig. 9(e) and (f) show the illumination distribution on the street from a luminaire with bended shaped microlens array, which lens off-center shift is in the y-direction. The effect is a change in the shape of illumination distribution which makes it more similar to the contour shape of the microlens unit. This illumination pattern improvement is followed by a cost in the optical efficiency, which decreases by the off-center shift.

5. Adaptive Optical Design Example

Consider a road with strong curve shape as shown in Fig. 10(a). In such a roadway two adjacent luminaries must provide an adaptive light distribution. Using LED luminaries to produce light patterns like those in Fig. 9(d)–(f), a hot fringe appears due to light overlapping between two luminaries, as

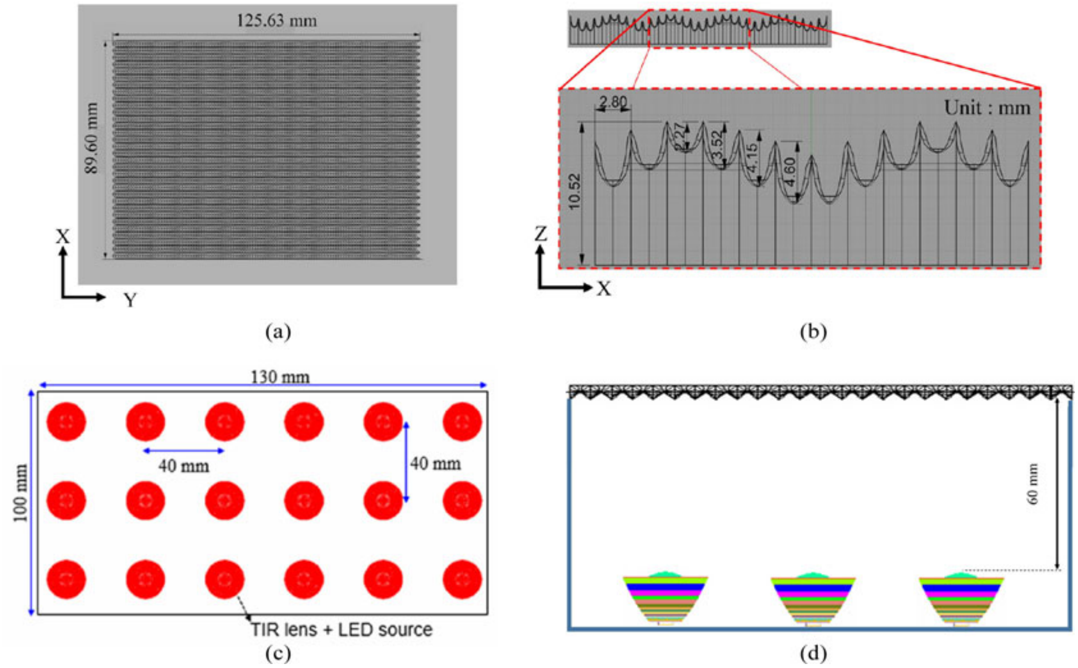

Fig. 12. Schematics showing the structure of adaptive LED luminaire analyzed in Fig. 11. (a) Top and (b) side views of the microlens array plate. (c) Top and (d) side views of LED array and the complete module.

shown in Fig. 10(a). This excess of illumination results in a waste of energy and a decrease of the illumination uniformity. Let us examine one possible solution by producing illumination distributions with light attenuation at the edges of each curved light pattern so that the hot fringe in the between may be reduced.

We figured out that this light attenuation may be achieved by designing a microlens array plate with non-homogenous lens depths as shown in Fig. 10(b). A microlens plate with different lens depths may redistribute luminous energy in the street, in this case by making the central part bright and sides soft. Fig. 10(c) shows the light patterns obtained by illuminating different regions of the microlens plate of Fig. 10(b) with perfect collimated light. We consider a microlens array with parameters of Fig. 9(e), 0.1 mm off-center, and H variable. We can see the improved optical performance of the LED luminaire using this microlens plate in Fig. 10(d), which shows how the illumination distribution becomes soft in its edges. This optical behavior may reduce the hot fringe and improve the performance if two adjacent luminaries are located like in Fig. 10(a).

But what about the shape of road. Let us consider the adaptation problem of the illumination distribution to the shape of the roadway. In particular, let us calculate the optical utilization factor (OUF) [19], which measures how much light is put inside the roadway or the target area. Fig. 11 shows a target area difficult to illuminate, which is highlighted in red color. It follows the roadway shape and adds one meter extension at the road edges for pedestrians. In order to generalize our analysis, we consider a complex roadway shape with a sharp curve. This roadway has an average width of 11 m, and pole height is 12 m. We consider two luminaire positions: with luminaire at the center of roadway, and placed at the road side with a luminaire arm length of 3 m. The adaptive illumination is achieved by a special microlens array design, which adapts the illumination to the shape of this curved roadway. This microlens profile is shown in Fig. 11, which we consider in two design variants: one with the original flat surface showing sharp endings, and the other is a modified version that cuts unnecessary sharp lens endings. The unsharp version is more efficient than the sharp one. The resulting OUF is quite high for a so curved shape road, and the illuminance

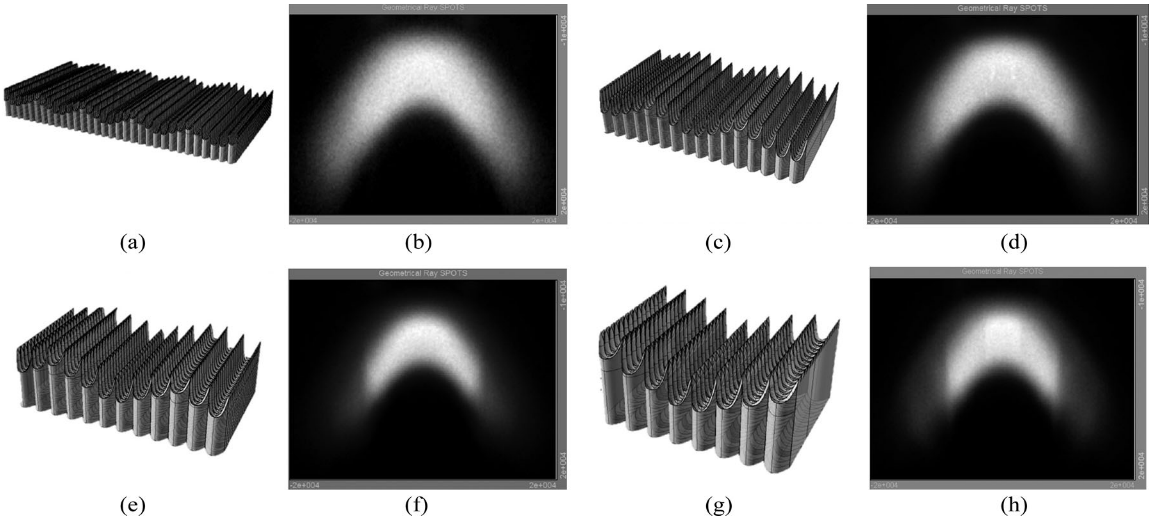

Fig. 13. Illumination distribution comparison due microlens arrays with four different sizes. (a) Original microlens structure and (b) its related light distribution on the roadway. (c) Double-size microlens structure and (d) its related light distribution on the roadway. (e) Triple-size microlens structure and (f) its related light distribution on the roadway. (g) Quadruple-size microlens structure and (h) its related light distribution on the roadway.

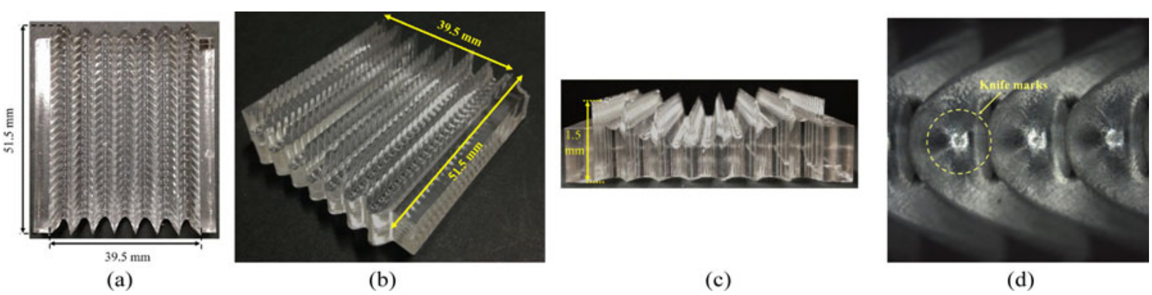

Fig. 14. Microlens array prototype manufactured by down-size molding. (a)Top view. (b) 3-D view. (c) Side view. (d) Zoom view.

levels are quite acceptable for standard values [2], [20]. The OUF is such cases are found more than 53%, which is even higher than 45% in a straight roadway with LED lighting [19]. Fig. 12 shows a detailed scheme of the adaptive LED luminaire that produces those light distributions shown in Fig. 11. In particular, top and side views of the microlens array plate, and the luminaire module are shown.

6. Prototype Construction and Experimental Confirmation

Because the lack of manufacturing resources at our laboratory, first we performed an analysis of the effect of microlens size. In particular, the practical issue of size scaling. Fig. 13 shows the effect of scaling the structure of microlens array for four scaled sizes, which are respectively original size, double size, triple size, and quadruple size. Note we include microlens parameters, but H is variable through the plate. The sizes of original-size microlens structure in three dimensions are 2.8 mm in length, 1 mm in width, and a variable size in height. The sizes of microlens structure with double-size magnification in three dimensions are 5.6 mm in length, 2 mm in width, and a double-size magnification in original height. The sizes of microlens structure with triple-size magnification in three dimensions are 8.4 mm in length, 3 mm in width, and a triple-size magnification in original

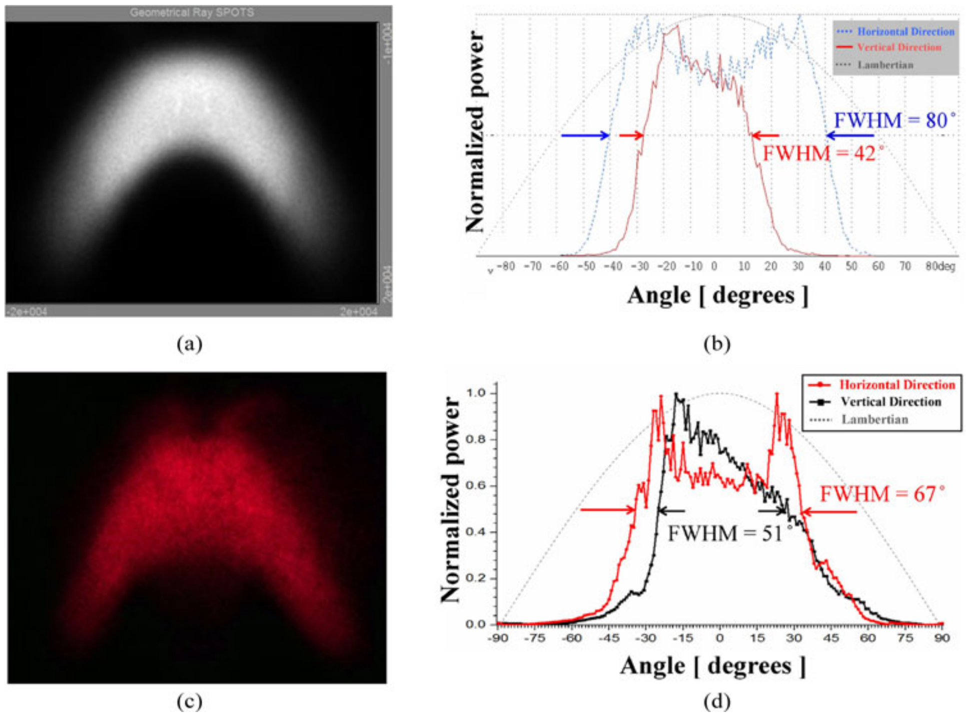

Fig. 15. Comparison between simulation and experiment using the microlens array prototype shown in Fig. 14. (a) Light distribution and (b) its divergence angles in the simulation. (c) Light distribution and (d) its divergence angles in the experiment.

height. The sizes of microlens structure with quadruple-size magnification in three dimensions are 11.2 mm in length, 4 mm in width, and a quadruple-size magnification in original height. The illumination distribution becomes less uniform and more localized when scaling up the original size.

We built a microlens array prototype, manufactured by down-size molding [18], as shown in Fig. 14. This first prototype is small, i.e. of size 51.5 mm $\times$ 39.5 mm $\times$ 1.5 mm. This is built in transparent glass with refractive index of 1.5. Fig. 14 shows several views of this prototype. The luminous distribution produced by this prototype is shown in Fig. 15, where the simulated illumination distribution is included for comparison. We can note the high similarity between simulations and experiment. The differences are attributed to manufacturing errors, in particular those small endings, like knife marks, shown in a zoom view in Fig. 14(d).

7. Conclusion

We have proposed, examined and confirmed the new concept of adaptive street lighting. This type of street lighting has the potential to reduce energy waste and light pollution by efficiently lighting roadways with arbitrary shapes. The proposed adaptive device is an LED lamp that delivers a light pattern with the shape of the road, which maximizes illumination performance. This luminaire adapts to the roadway just by simply replacing the cover plate, which is a structured microlens array sheet. Different aperture microlens units produce different shape light patterns. The adaptive mechanism is simple and effective: LED light is first collimated and then efficiently distributed on a freeform roadway by the special microlens array sheet.

We presented an extensive analysis of the lighting adaptability of the proposed luminaire. In particular, we analyzed the effect of key structural parameters of the microlens array in the optical performance of the LED luminaire. The analysis focused on the illumination distribution and the optical efficiency by using Monte Carlo ray tracing. We analyzed how the main microlens structural parameters changed the shape and size of the delivered illumination distribution on the road.

Finally we examined a design example of adaptive street lighting for a sharp curved roadway. This design used a non-homogenous lens depth distribution. In order to test the concept, we constructed a prototype of adaptive street lighting set in our lab. The luminaire was scale constructed using down-size molding for the microlens array.

Since the microlens aperture shape strongly determines the illumination pattern shape, our approach may be very suitable for future developments of dynamic adaptive lighting by flexible microlenses arrays with deformable apertures, or even by automatic mechanisms for interchanging plates.

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