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Beam Shaping of LED Luminaries using Condenser Lens

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Abstract- Use of LEDs as light source is increasing tremendously. In every field they have replaced CFL/CFT. In many applications it has become essential to have focused uniform illumination. In such cases it is achieved by using secondary optics. The illumination pattern can be changed by changing either LEDs or optics which is not possible always. In this paper concept of adjustable beam shaper, achieved by changing polar distribution of LED cluster using condenser lens to generate required illumination pattern is put forward. A condenser lens along with diffuser is used to alter and project an input light beam into required angular pattern. It leads to the change in the output illumination pattern. One can optimize LED and lens parameters for required pattern.

Index Terms - Adjustable beam shaper, LED illumination, condenser lens, illumination pattern.

1. INTRODUCTION:

Now a days LEDs are found to be better option as light source due to various advantages of low power consumption, long life time, environment friendly etc. and it's illumination application areas are widening from traffic light source to automotive lighting, backlighting of LCD, mobile or T.V., interior and exterior lighting, street lighting etc.[1,2]. In all these applications light luminaries consists of cluster of LEDs.The light output of such luminaries depends on characteristics of individual LED as well as on geometry of cluster and target to source distance. .LED has peculiar directional radiation pattern which decides intensity distribution on target plane. Once luminary is constructed output characteristics of illumination system such as uniformity, intensity level, area of coverage etc. are fixed. Often there is need to alter these parameters at user end so that designed luminaries may be used either for spot lighting or for general lighting. It can be achieved either by changing individual LED or cluster configuration which is not physically possible. Alternate solution to this problem is to have some flexible arrangement inside the luminaries by which we are able to alter the characteristic of luminaries without changing components. Focusing on this goal a novel concept of changing polar distribution of LED cluster using condenser lens to generate required illumination pattern is put forward.

It is not uncommon to use secondary optics with LED source to increase uniformity and efficiency of system. It is used to convert spatially incoherent light into required shape of light beam. Until now, people have successfully tried spatial filter [3], diffuser [4] or specular reflectors, diffractive or refractive elements such as TIR (total internal reflection) lens, free-form lens[5], microlens arrays [6] for shaping the radiation pattern of LED and to obtain an application dependent divergence angle.

In this paper we proposed a adjustable beam shaper of LED luminaries using secondary optics. A condenser lens along with diffuser is used to alter and project an input light beam into required angular pattern. Introduction of lens and diffuser in front of an LED optical source changes beam angle of luminaries and hence intensity patterns without changing cluster geometry or individual LED. Mechanical assembly attached to cluster assembly can move the cluster horizontally. It leads to the change in the output illumination pattern. By optimizing LED and lens parameters the cluster movement can be restricted within luminaries. The interdependency of parameters of LED source, illumination system and condenser lens on the beam shaping process by analytical equations is discussed in the paper.

2. DEFINITION OF PROBLEM

Consider an illumination system consisting of LED source and a condenser lens. Parallel to source plane a target plane is placed. When illuminated, the source creates certain illumination pattern on the target. Our objective is to change an illumination pattern by movement of source plane. The intensity distribution of the system depends on three factors:
1) Geometrical structure of LED source cluster: Here set of parameters are number of LEDs, their related position, polar and spectral characteristic of individual.
2) Secondary optics: In a condenser lens system the parameters are focal length, aperture thickness and distance from source.

3) The source to target distance is third parameter.

3. MODELING

3.1 Modeling of single source

The LED's radiation patterns can be modeled as far-field, mid-field and near-field depending upon target distance [7]. Far field zone begins at a target distance greater than five times of dimension of the light source[8]. In this zone source can be considered as point source.

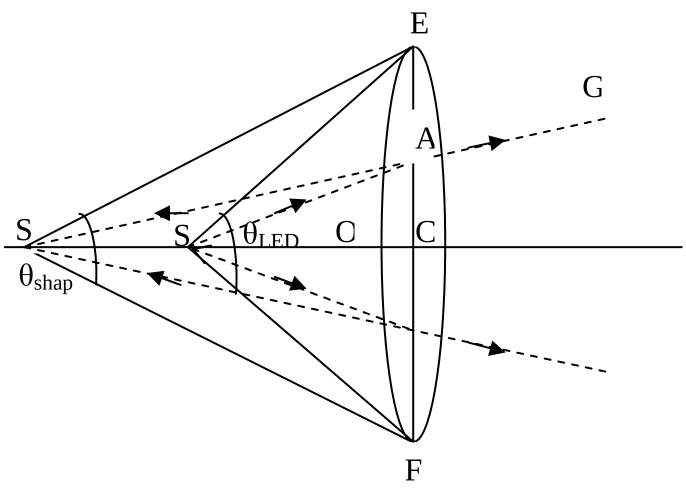


Figure 1. Modelling of LED and Lens System

Polar distribution of LED radiation typically show Lambersian pattern having rotationally symmetric radiation patterns with single intensity peak along the optical axis of LED.It is specified by full width at half maximum angle (FWHM). It is the angle at which radiated intensity is equal to half of its maximum, maximum being occurred along 0°.

As shown in figure 1, an LED point source 'S' be placed on the optical axis. A condenser lens is placed at a distance 'O' from it. Let ray SA is incident on lens. After refraction it follows the path AG. Extends of light rays from LED striking the lens is confined within the cone of an angle equal to FWHM. The light rays deviates away from the optical axis if source distance is less than the focal length of lens. If we extend the emergent ray AG, backward it meets the optical axis at S^1. The ray AS^1 makes an angle θ_{shaped} to optical axis. Virtual image is formed on the same side as that of the source at position 'S^1'. Thus introduction of lens modifies effective position of source and FWHM of LED as θ_{shaped}.

$$\tan\left(\theta_{\text{LED}}\ /\ 2\right) = \frac{y}{\text{O}} \quad \text{---------}\ (1)$$

$$\tan\left(\theta_{\text{shaped}}\ /\ 2\right) = \frac{\text{y}}{\text{O}'} \quad \text{---------}\ (2)$$

By 1 and 2 we can write

$$\tan\left(\theta_{\text{shaped}} / 2\right) \times \text{O}' = \tan\left(\theta_{\text{LED}} / 2\right) \times \text{O} \quad \text{--------}\ (3)$$

$$\theta_{\text{shaped}} = 2 \times \tan^{-1}\left(\tan\left(\theta_{\text{LED}} / 2\right) \times \frac{\text{O}}{\text{O}'}\right) \quad \text{--------}\ (4)$$

Equation (4) states that modified LED angle depends on FWHM of LED, source distance and image distance. In terms of focal length, equation (4) can be written as

$$\frac{1}{\text{O}} + \frac{1}{\text{O}'} = \frac{1}{f} \quad \text{[Gauss's formula] i. e.}$$

$$\text{O}' = \frac{f \times \text{O}}{\text{O} - f} \quad \text{------}\ (5)$$

$$\theta_{\text{shaped}} = 2 \times \tan^{-1}\left(\tan\left(\theta_{\text{LED}} / 2\right) \times \frac{\left(\text{O} - f\right)}{f}\right) \quad \text{----------}\ (6)$$

Equation (6) gives modified FWHM of source which depends on FWHM of LED, source distance and focal length 'f ' of lens.

Equation (6) is valid as long as {O * tan (θ_{FWHM}/2)}is less than or equal to A/2. Under this condition all the rays emitted from LED source are confined within the cone of aperture. If above condition is not satisfied then some of the rays fall outside the cone. New FWHM will be less than the expected and even the light intensity falling on the target surface due to LED source will change. This puts upper limit on maximum FWHM that can be obtained for a given set of FWHM of LED, source distance and focal length 'f' of lens. Maximum FWHM is obtained when extreme light rays strike at C and D points i.e. y = A / 2. Thus from equation (2) maximum possible FWHM is

$$\theta_{shaped_{maximum}} = 2 \times \tan^{-1}\left(\frac{\text{A}/2}{\text{O}'}\right) = \tan^{-1}\left(\frac{\text{A}/2 \times \text{abs}\left(\text{O} - f\right)}{f \times \text{O}}\right) \quad \text{--------}\ (7)$$

In both the cases modified angle is less than the original if source is placed between focus point and center of lens.

B] To obtain variable FWHM source : Our objective is to have variable FWHM of source between θ_1 to θ_2. Equation 6 and 7 reveals that to achieve this one can either change LED source, source distance or focal length. It's convenient to change source distance since other two demands change of components. Thus preferable solution is the movable source.

Let us consider at object distance O_1, FWHM be θ_1 and that at O_2, FWHM be θ_2.

We consider generalized case of modified FWHM given by equation (6).

$$\frac{\tan(\theta_1/2)+\tan(\theta_{LED}/2)}{\tan(\theta_{LED}/2)}=\frac{O_1}{f};$$

$$\frac{\tan(\theta_2/2)+\tan(\theta_{LED}/2)}{\tan(\theta_{LED}/2)}=\frac{O_2}{f} \quad \text{------- (8)}$$

$$\frac{\tan(\theta_1/2)-\tan(\theta_2/2)}{\tan(\theta_{LED}/2)}=\frac{\Delta O}{f} \quad \text{-------- (9)}$$

where $\Delta O = O_1 - O_2$.

Equation (9) reveals that variable FWHM is possible by changing object distance from center of lens of focal length 'f'. It can be achieved by changing position of source from O_1 to O_2. At position O_1source will have FWHM of θ_1 and at position O_2 source has FWHM of θ_2.Movement of source betweenO_1 to O_2generates spot light with variable FWHM fromθ_1 to θ_2.

C] Design parameters of lens:

Typical parameters necessary to design a lens for LED optical source include focal length, aperture and thickness. These lens parameters are calculated as:

i)The thickness of lens:
Thickness of lens, t = *l*(BA) = 2 (r – 2f)

$$t=2\left(\sqrt{4f^2+\frac{A^2}{4}}-2f\right) \quad \text{----------- (10)}$$

since $r^2 = (2f)^2 + (A/2)^2$

It is necessary to keep the lens thickness as small as possible.

ii) The focal length of lens : Using lens maker formula one can find focal length for required change in object distance.

$$\frac{1}{f}=\frac{1}{O}+\frac{1}{O'}$$

iii) Aperture of lens:

$$A=2\times O\times\tan(\theta_{LED}/2)$$

3.2 Modeling of source array:

Since for lighting application single LED falls short for providing required lux level, often cluster of LEDs is required. Let us see effect of condenser lens on such cluster.

Consider a coplanar surface parallel to lens with randomly placed LEDs. Let there be 'n' number of LEDs with i th LED having coordinates (x_i,y_i). Since source plane is parallel to lens, x–coordinate of each LED is same. The effective FWHM of multielement LED source is decided by FWHM of peripheral LEDs. As long as position of all LEDs is such that their FWHM cones lie within acceptable limit given by equation (7) new FWHM of source is same as θ_{new} of equation (6). In this case source has maximum efficiency. One of the LEDs on both the sides must have y- coordinate as

$$\therefore\ y=\pm\left(\frac{A}{2}-\frac{f\times O}{O-f}\right)\tan\theta_{shaped}$$

The problem arises if y- coordinate of one of the LEDs is greater than above calculated value. In this case new FWHM will be less than the required one and has value

$$\theta_{shaped}{}' = \tan^{-1}\left(\left(\frac{A}{2}-y\right)\times\frac{(O-f)}{f\ O}\right)$$

3.3 Effect of Lens on LED parameters:

Introducing lens in front of LED source affects three parameters of optical system.

1) Virtual image of source is formed at distance O' calculated using equation (5). The image will further act as a source for optical system. Thus the effective position of source has been changed.

2) FWHM of LED gets modified as per equation (6) or (7) which means that the radiation pattern of LED changes. Change in spatial characteristics of LED generates different illumination pattern on target surface. If object is moved away from lens then converging effect observes and illuminated surface area decreases with increase in maximum intensity level.

3) Insertion of lens between source and target also affects the effective lumen output of individual LED. If a light source emits 1 candela of luminous intensity uniformly across a solid angle of 1 steradian, the total luminous flux emitted into that angle is 1 lumen. The relationship between lumen and candela is given by

Lumen = candela × solid angle in steradian

Solid angle in steradian = 2×Π× [1- cos (FWHM/ 2)]

Focal length	Required change in object distance (mm)	Thickness (cm)
10	0.30	2.38
50	1.49	0.49
100	2.99	0.25
150	4.48	0.16
200	5.97	0.12
500	14.9	4.98

Let LED with θ FWHM has intensity output of ‘I’ lumen. When lens is introduced in the path modified FWHM is θ_{new} and lumen output changes to

$$I_{new} = I \times \frac{(1 - \cos(\theta/2))}{(1 - \cos(\theta_{new}/2))}$$

Above three parameters need to be considered while comparing the performance of an optical system with and without lens. The system analysis is carried out by the software written using analytical equations based on spatial and spectral characteristics of LEDs. The simulated results are discussed further.

4. RESULT AND DISCUSSION:

The design parameters of lens such as focal length, aperture and thickness, object distance and FWHM of source are interdependent on each other. Their interdependency is discussed here.The simulated readings are given for variable FWHM of 15 – 60. For simulation “OPTSIMLED”, package is used [9].

4.1 *Effect of FWHM of source:*

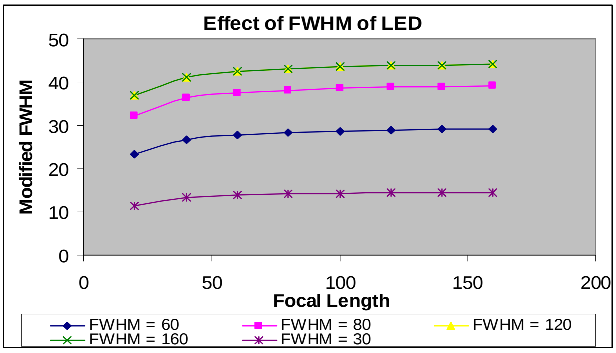
Let Aperture = 14 mm, Focal length = 100mm

FWHM	Required change in object distance (mm)	Thickness (mm)
10	646.7	0.25
30	202.3	0.25
60	86.8	0.25
120	20.2	0.25
160	2.99	0.25

Result shows that if initially source has smaller FWHM then to achieve variation in source FWHM from 15 – 60, large variation in object distance is needed. Practically upto 10mm variation is possible. That means large FWHM is preferable.

4.2 *Effect of Focal length of lens:*

Let Aperture = 14 mm, FWHM = 160.



Lens of higher focal length demands large variation in object distance. But at the same time thickness of lens decreases. Thus for thin lens design focal length is a crucial parameter.

4.3 *Effect of Aperture of lens:*

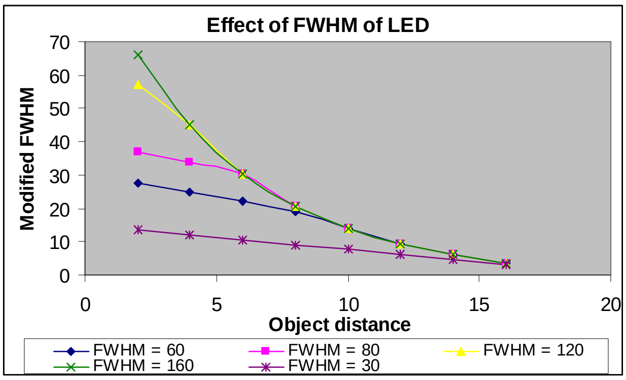
Let FWHM = 160 , Focal length = 100mm.

Aperture of Lens	Required change in object distance (mm)	Thickness (mm)
5	**2.99**	**3.125**
7	**2.99**	**6.125**
9	**2.99**	**0.101**
11	**2.99**	**0.151**
12	**2.99**	**0.17996**
13	**2.99**	**0.2112**
14	**2.99**	**0.2449**

4.4 Variable *source distance*

A = 10 ; focal length = 20 ; source on optical axis

Graph shows dependency of modified FWHM on object distance. As source is moving towards focal point new FWHM goes on decreasing. If source has

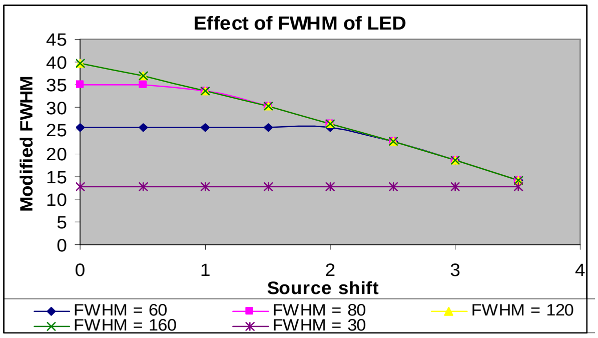


large FWHM then modified FWHM is larger for smaller object distance and for larger distances it remains almost same. It means that if large source distance is permissible narrow angle LEDs can be used as source otherwise for less source distance wide angle LEDs are required.

4.5 Variable focal length

If we hold the distance between the lens and source fixed and let source be within focal length, the relationship between the modified FWHM and focal length of lens is shown in figure.
A = 10; source on optical axis at 5.

Graph shows that increase in focal length of lens increases new FWHM irrespective of FWHM of



source if source is at 20 and shows variation if source is at 5.

4.6 Variable source distance

A = 10; focal length = 30; source above optical axis and x-cord. = 5

For small FWHM of LED modified FWHM remains constant irrespective of y-position of source. For wide angle LEDs since all the rays are not confined within the cone modified FWHM goes on decreasing.

4.7 Illumination system performance:

Simulated results given are forcircular LED ring source illuminating a target plane of 1m X 1m dimension. Source assumes 7 LEDs each of 100lm and FWHM of 125°. The distance between source and target plane is 1m.

Lens of aperture 70mmhas been introduced between source and target at distance 'x' from source to achieve new FWHM of 15° and 60°. Following table gives values of source distances required for three different focal lengths and for two different LED FWHM angles.

Focal Length (mm)	**FWHM of LED**	**Source distance from lens (mm) for 15° FWHM**	**Source distance from lens (mm) for FWHM of 60°**
100	125	18.2	41.40
	160	6.17	14.03
140	125	18.2	50.68
	160	6.17	17.17
200	125	18.2	64.6
	160	6.17	21.89

The illumination pattern, intensity contours and analysis values are simulated for this configuration. (far-field distribution)

	Without lens		**For 60°**		**For 15°**	
	125	160	125	160	125	160
Uniformity ratio	1.25	1.21	1.58	1.59	10.7	12.0
Diversity ratio	1.87	1.72	3.73	3.85	10.1	36.0
Average lux	19.1	15.4	121.	190	984	1511
Max. intensity (lx)	26.7	20.9	214	338	11258	19191
Min. intensity (lx)	12.3	12.3	12.3	12.3	0.16	0.1

(Note :Maximum intensity is the intensity at center of the target surface.)

5. CONCLUSION

An adjustable beam shaper of LED luminaries using secondary optics is demonstrated in the paper. A condenser lens along with diffuser is used to alter and project an input light beam into required angular pattern. Introduction of lens and diffuser in front of an LED optical source changes beam angle of luminaries and hence intensity patterns without changing cluster geometry or individual LED. Mathematically interdependency of lens and LED parameters has been illustrated. It has also been tested using simulation. The LED and lens parameters can be optimized to obtain desired uniform pattern.

REFERENCES

[1] V. Derlofske and M. W. McColgan, 2002, “White LED sources for vehicleforward lighting,” *Proc. SPIE,* 4776, 195–205.

[2] K. Wang, X. B. Luo, Z. Y. Liu, B. Zhou, Z. Y. Gan, and S. Liu, 2008, “Optical analysis of an 80-W light-emitting-diode street lamp,” *Opt.Eng.*, 47_1_, 013002..

[3] S. Wilcken, Nov 1996, ‘‘Packaging holds the key to new LEDs’ success,’’ Photonics Spectra 120–122..

[4] L.-Y.-T. Lin-H-Y and W-D Tyan, 1996, ‘‘High-gain, wide-viewing-angle and null-hot-spot optical diffuser useful for display screen application,’’ *Proc. SPIE* 2892,64–71.

[5] Y. Luo, Z. Feng, Y. Han, and H. Li,2010, “Design of compact and smooth free-form optical system with uniform illuminance for LED source,” Opt. Express 18(9), 9055–9063.

[6] Alexander Buttner, Uwe D. Zeitner, (October 2002), “Wave optical analysis of light-emitting diode beam shaping using microlens arrays”, Opt. Eng.41(10) 2393–2401.

[7] C. C. Sun, W. T. Chien, I. Moreno, C. C. Hsieh, and Y. C. Lo, (2009), “Analysis of the far-field region of LEDs,” Opt.Express 17(16), 13918–13927.

[8] I. Moreno, and C. C. Sun, (2008), “LED array: where does far-field begin?” Proc. SPIE 7058, 70580R–70580R–9.

[9] D. V. Ramane and A.D. Shaligram, 2011 “Modeling and Simulation of Multielement LED Source”, J. Light and Visual Environment, vol.35, No 1, 1-8.