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Abstract. Multicolor multielement LED luminaries have wide applications in decorative, display, and medical domain etc. It can provide light with variable intensity and spectral content. One such application of designing of multispectral reading light for patients having low visual acuities is reported here. Paper describes microcontroller based reading light system for such patients. Mechanical, electronic, and optical assemblies required for the system are explained with more focus on optical assembly. Number of LEDs, their relative placement, spatial and spectral characteristics of individual and source to target plane distance decide spatial and spectral uniformity of illumination. Fabricated luminaire consists of 90 low power LEDs of red, orange, yellow, green, and aqua arranged in six rows. The reading plane can be illuminated with variable intensity and color by changing current through LEDs. These values are adjusted and stored according to comfort level of individual patient. [DOI: 10.1117/1.JBO.17.1.018002]

Keywords: Multispectral LED luminaire; patients with low vision; spatial and spectral uniformity.

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1 Introduction

Color-LEDs have enormous potential in lighting applications. An LED light source consisting of color-LEDs can provide a compact light source with unique features such as instant illuminance level and color variability. It can produce various color shades including white light.[1–3] Different LED source configurations allow shaping of the light spectrum and illumination pattern. It is because the spectral power distribution of the light emitted by LED is narrowly tuned and hence the light is strongly colored.[4] Dong et al. have used an analytical model of color mixing and have designed a ring source consisting of RGB LEDs for machine vision application.[5] Chen et al. presented an optimal design of a multiple-LED reading light system using a secondary optics. The groove angles of the Fresnel lens are adjusted so as to maximize the illuminance in a specified reading surface while maintaining the uniformity.[6] A reading application reported here demands illumination with adjustable color and illuminance. Design of an multielement LED source for the same is discussed in the present work.

The application discussed here is the design of a reading light system for individuals with low vision. Loss of visual field or contrast results in an impaired performance at work or daily chores and even at leisure. Lehon found that normal man requires upto 1038 lx on a reading table for comfortable reading while visually impaired people need more bright light having illuminance of 1802 lx.[7] In 1984, the lighting requirements of a cohort of visually impaired children for performing a reading task was investigated.[8] Southall found that reading speed remains constant with an increase in luminance for fully sighted children, while speed increases with an increase in illuminance level for partially sighted children.

It was further found that the reading ability of such people is also associated with the spectral content of the illumination system. The light sensitive cells of the retina of eye are of two kinds: rods and cones. Rods are very sensitive to intensity but do not distinguish colors well. Cones are about a thousand times less sensitive to illuminance than rods, but they perceive colors. Exposure to certain colors can cause discomfort. This is due to the hypersensitivity of particular cones in the eye. Relief from symptoms is attained by removing or adequately reducing the spectral component of the illumination source associated with the hypersensitive cones. However, the symptoms are specific to an individual. It was reported by Halonen et al. in 1994 that visual acuity of retinitis pigmentosa patients had increased when the blue part of the visible spectrum was decreased.[9] Several studies[10–13] have suggested that blue light waves may be especially toxic to those who are prone to macular problems.

Thus, research shows that preferred spectral content and illuminance levels for comfortable reading vary from person to person. There is a need for an illumination system with adjustable illuminance and color.

Reading performance can be enhanced in those with low vision with the aid of optical low vision aids. Such aids have internal illumination, often comprising LEDs. Some low vision aid users also use magnifying spectacles, and for these individuals, external illumination is crucial. Different light sources having different spectral power distribution are used to produce different colored illumination. Further spectral variation is achieved by fitting a filter, available in certain standard specifications, on a conventional light source. This is a 'static' and 'passive' solution. A filter has fixed characteristic that cannot be modified to better suit individual needs. A more 'dynamic' and 'active' approach is to alter the spectral output of the light source itself instead of using a filter to mask a light source. This is

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realized by the construction of a composite light source. The reported composite source contains clusters of LEDs of different spectral characteristics, such that when driven together, they generate white light. By adjusting the individual contributions of primary light sources, the spectral content of the composite system is adjusted to best suit the needs of individual users.

2 Design Goals

The design goals of the illumination system for a reading task application for persons with low vision are finalized. Considering A4 size paper dimensions (297×210 mm^2), the reading area is fixed as 320×280 mm^2 and the source is placed at approximately 80 mm from the target area to permit head space for the reader. The other specifications are as follows:

1. Adjustable spectral contents of source with wavelengths less than blue color wavelength (<470 nm) not allowed
2. Adjustable intensity level within limit 150 to 1000 lx
3. Illuminance Uniformity greater than 60%
4. No glare i.e. absence of hot spots (areas with illuminance >850 lx) should be avoided
5. High contrast ratio greater than 0.60

To fulfill the above requirements the composite light source consisting of multicolor LED is proposed.

3 LED Light Source Design

The design of a reading system involves the design of mechanical assembly, electronic control, and light source. In the present paper, light source design is focused. The designing of the light source is critical as the output depends upon the number of parameters such as the number of LEDs, their relative placement, spatial and spectral characteristics, color sequence, tilt angle and height from target plane.[14,15]

Designing of the LED source is carried out in two steps: 1. selection of LED color 2. finalizing number of LEDs and their relative placement.

3.1 *Selection of LED Colors*

All the commercially available light sources have a static spectral output. However, the requirement for this project is to have the composite system which allows adjustment of its spectral output over visible range of 400 to 700 nm. Moreover, wavelengths less than 470 nm are not suitable for those with low vision. To achieve this, a primary light source of spectral bandwidth smaller than that of the composite system is required. Indeed the narrower the bandwidth of the primary light source, the greater the resolution of control over the spectral content of the composite source. Both the incandescent as well as the fluorescent light sources have broad spectral emissions across the visible spectrum that implicitly disqualify them as appropriate options for the primary light source. On the contrary, the narrow band spectral output of monochromatic LED makes it perfect for use in a composite system. Their spectral power distribution follows Gaussian function with single peak wavelength and full power spectral width (FWHM) dependent on color as shown in Fig. 1.

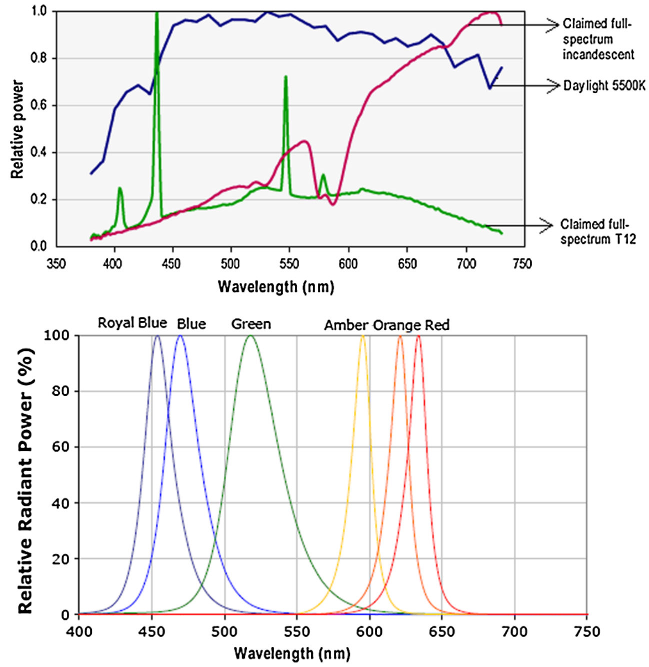


Fig. 1 Spectral power distribution of commercial sources and color LEDs. (Color online only.)

The selection of LEDs as the source has other advantages as well. These are available with a wide variety of peak wavelengths. It is easy to control the source flux by controlling the current flowing through it. Because of the small size, it is possible to construct a compact source consisting of multiple LEDs with a different peak wavelength. They are handy for practical applications.[16] Long life, energy efficient, pollution free, and lower maintenance cost are further advantages.

If more than one LED with different peak wavelengths constitutes a source, then the spectral content of the illuminated pattern is the sum of the spectral content of the individual primary light sources and accordingly, the color of illumination changes. The spectral contribution of each LED must be such that together they generate a white light spectrum, and when the luminance level of individual LEDs changes, it produces different color illumination. LEDs were chosen such that their spectral content facilitated maximum spectral resolution control and maximum spectral coverage. If FWHM of one LED is 25 nm, then to cover visible spectrum of 450 to 700 nm, five LED colors would be required.

Further, the selection of LED color is based on the consideration of glare and contrast. Technically, relief from glare can be achieved by filtering the short-to-medium wavelengths of the visible spectrum (blue, green, yellow) which allows only the longer wavelengths to reach the retina. For glare reduction, amber, orange, plum, green, and gray colors are most effective.[17]

Contrast enhancement is also a function of the shorter wavelengths, and orange, yellow, and amber colors are most effective. All of these have the effect of highlighting visual distinction and increasing contrast.

Thus, the preferred light source must have wavelength greater than 470 nm; use of orange, amber, yellow, green, plum, and gray colors enhance reading quality as it improves contrast and reduces glare. However, plum and gray color-LEDs are not available. Since the difference between peak wavelengths of

Table 1 Source specifications.

LED Part number	LED Color	Dominant wavelength (nm)	FWHM (nm)	Source flux		View Angle (°)
				mcd	lumen	
RL5–R8030	Red	628	20	8000	1.71	30
RL5–O4030	Orange	605	20	4000	0.86	30
RL5–Y5030	Yellow	595	15.96	5000	1.07	30
RL5–G5030	Green	525	25	5000	1.07	30
RL5–A7032	Aqua	507	29.86	7000	1.50	32

amber and yellow is less than 20 nm, the use of one LED is sufficient. Therefore, orange, yellow, and green colors are chosen. Furthermore, to cover wavelengths at extreme ends of the spectrum, red and aqua are selected.

These days, high power LEDs are available. However, removal of heat generated is considered as one of the major issues. On the contrary, use of low power LEDs reduces the thermal management considerably. Moreover, with a larger number of LEDs being used, there is sufficient flexibility available for adjustment in the illuminance and color mixing. Super bright LEDs are available in various colors with narrow band spectral emission described by FWHM of approximately 15 to 30 nm. This means that the spectral spread of each LED is approximately 80 nm to 100 nm. Optical specifications of five selected low power LEDs are given in Table 1 and the spectral power distribution plots using Gaussian equation are shown in Fig. 2.

There is a hole in the spectrum at 570 nm because of the lack of commercial LEDs at this wavelength. To fill up this gap, one can use warm white LEDs on the panel. Marginal blue contents arising need to be removed using blue wavelength filter.

3.2 *Number of LEDs*

After the selection of LEDs, the next step in designing is the number of LEDs required to achieve the design goals. Lumen required on target plane is

$$\text{Target lumen} = \text{Target lux} \times \text{Target area (in m}^2\text{)}$$
$$= 850 \times 0.28 \times 0.32 = 76.16 \text{ lumen.}$$

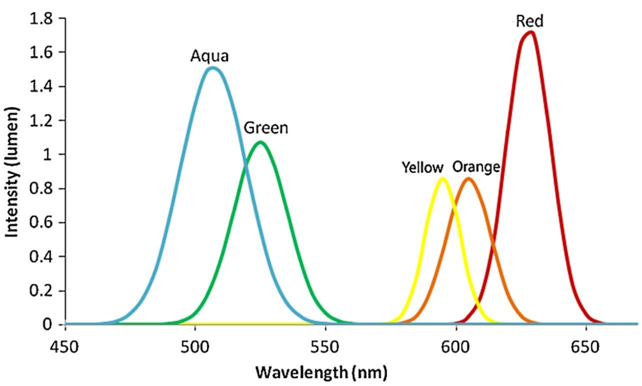


Fig. 2 Spectral power distribution of LEDs used for design. (Color online only.)

Thus, source flux of minimum 76.16 lumen is required. However, practically, source flux of higher value is needed because of optical and thermal efficiencies of the source system. These efficiencies are normally 91% and 85%.

$$\text{Source lumen needed} = \text{Target lumen}/(\text{Optical efficiency} \times \text{Thermal efficiency})$$
$$= 76.16/(91\% \times 85\%) = 99 \text{ lm.}$$

Thus, to generate 850 lx on a target plane of dimension 320×280 mm^2, the total source flux required is 99 lumen. The selected LED part numbers of super bright are in the range of 0.86 to 1.7 lumen [Table 1]. It means at least 90 LEDs are required.

3.3 *Placement of LEDs*

The placement of LEDs is critical. Various source geometries like rectangular, ring, linear, and triangular are discussed by Moreno et al. and has specific application domain.[18] For rectangular target surface illumination, ring and rectangular geometries are more suitable. The array of 90 LEDs is arranged in rectangular as well as ring form. The illumination performance of these are tested using the simulation tool OPTSIMLED.[19] The tool accepts multielement LED source and analyses it for illuminance level, uniformity, illuminance distribution, and color pattern based on individual LED characteristics and its geometrical position. Based on simulation results, rectangular shaped array is finalized as it was giving better illuminance uniformity. Further source parameters and geometrical details are optimized using the method described in reference.[14] The optimized source configuration is described here.

Five types of color LEDs mentioned above are selected for luminaire formation. These are arranged in 6 rows with 15 LEDs in one row (Fig. 3). The horizontal and vertical distance between centers of two neighboring LEDs is 10 mm. In the first row, LEDs are arranged in decreasing order of wavelengths: red, orange, yellow, green, and aqua. The second row sequence starts with yellow followed by green, aqua, red, and orange. The third row sequence is aqua, red, orange, yellow, and green. The fourth sequence is: orange, yellow, green, aqua, red, while that of the fifth is green, aqua, red, orange, and yellow. The sixth one is same as the first one.

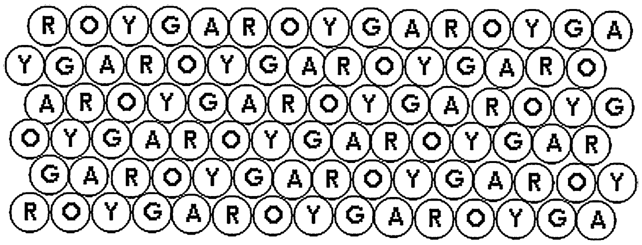


Fig. 3 Luminaire structure with color-LEDs.

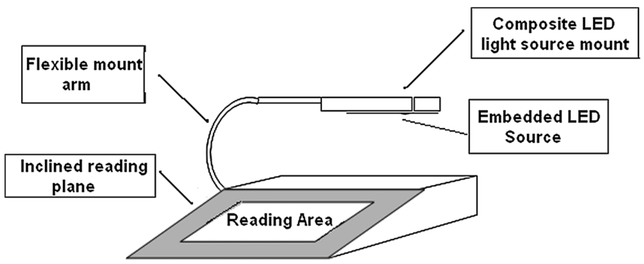


Fig. 4 Reading system assembly for individuals with low vision.

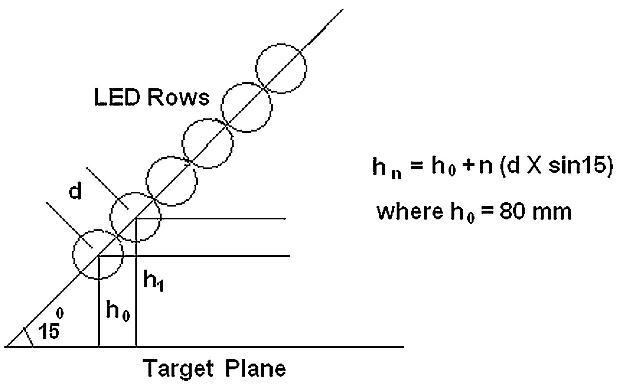


Fig. 5 Inclined source plane changes height of each row from target surface.

The mechanical assembly of the reading system is shown in Fig. 4. The composite light source consisting of 90 LEDs is mounted within a rectangular lamp housing of dimension 160 mm × 60 mm. The lamp housing is fitted to a reading board or panel by a flexible arm, to allow for manual adjustment of the target area. The reading board is a large panel of dimension 400×500 mm^2, inclined at about 15-deg to the table.

Because of the inclination angle of 15-deg, the source-target height of each row changes as shown in Fig. 5. The heights of six rows of sources from target plane are 80, 82.6, 85.2, 87.8, 90.4, and 93 mm, respectively. The detailed geometrical structure is tabularized in Table 2.

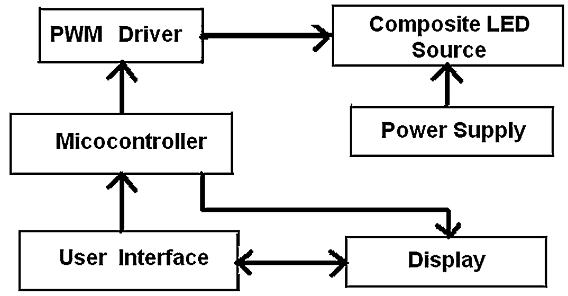


Fig. 6 Block diagram of electronic assembly.

4 Results

The reading system is driven by an electronic control assembly which controls switching and dimming of the LEDs. Block diagram of electronic assembly is shown in Fig. 6.

The current through LED is controlled by driving the source by pulse width modulator (PWM) circuit. Microcontroller accepts input from the user as per the requirement of an individual and sets the pulse width accordingly. This in turn controls illumination of multielement LED system. The pulse width setting is different for different persons. For setting pulse width, initially the idea is that the console is provided to the user. The operator essentially alters the illumination in an interactive way. Two parameters are to be set—illuminance level and spectral contents so as to best suit the need of a person with low vision. The setting which the user finds the most comfortable is recorded and used for the individual, each time, he uses the system.

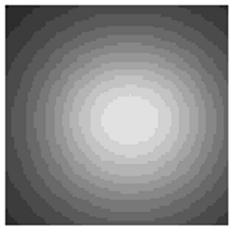
It may be noted that the results are of reading light illuminating the reading plane under normal room light condition.

Table 2 Geometrical configuration of source.

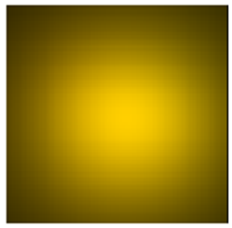
			X-Coordinates of 15 sources in a row														
Row no.	Y-Coordinate	Height	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15
1	5	80	15	25	35	45	55	65	75	85	95	105	115	125	135	145	155
2	15	82.6	5	15	25	35	45	55	65	75	85	95	105	115	125	135	145
3	25	85.4	15	25	35	45	55	65	75	85	95	105	115	125	135	145	155
4	35	87.8	5	15	25	35	45	55	65	75	85	95	105	115	125	135	145
5	45	90.4	15	25	35	45	55	65	75	85	95	105	115	125	135	145	155
6	55	96.0	5	15	25	35	45	55	65	75	85	95	105	115	125	135	145

Source Wattage (W)	3.06
System Efficacy (lumen / W)	35.27
Uniformity of illuminance	72.37
Average Lux on surface	902
Maximum Intensity in Lux	1246
Minimum Intensity in Lux	274

(a)



(b)



(c)

Fig. 7 Illumination pattern and illuminance distribution for all LEDs 100% ON. (Color online only.)

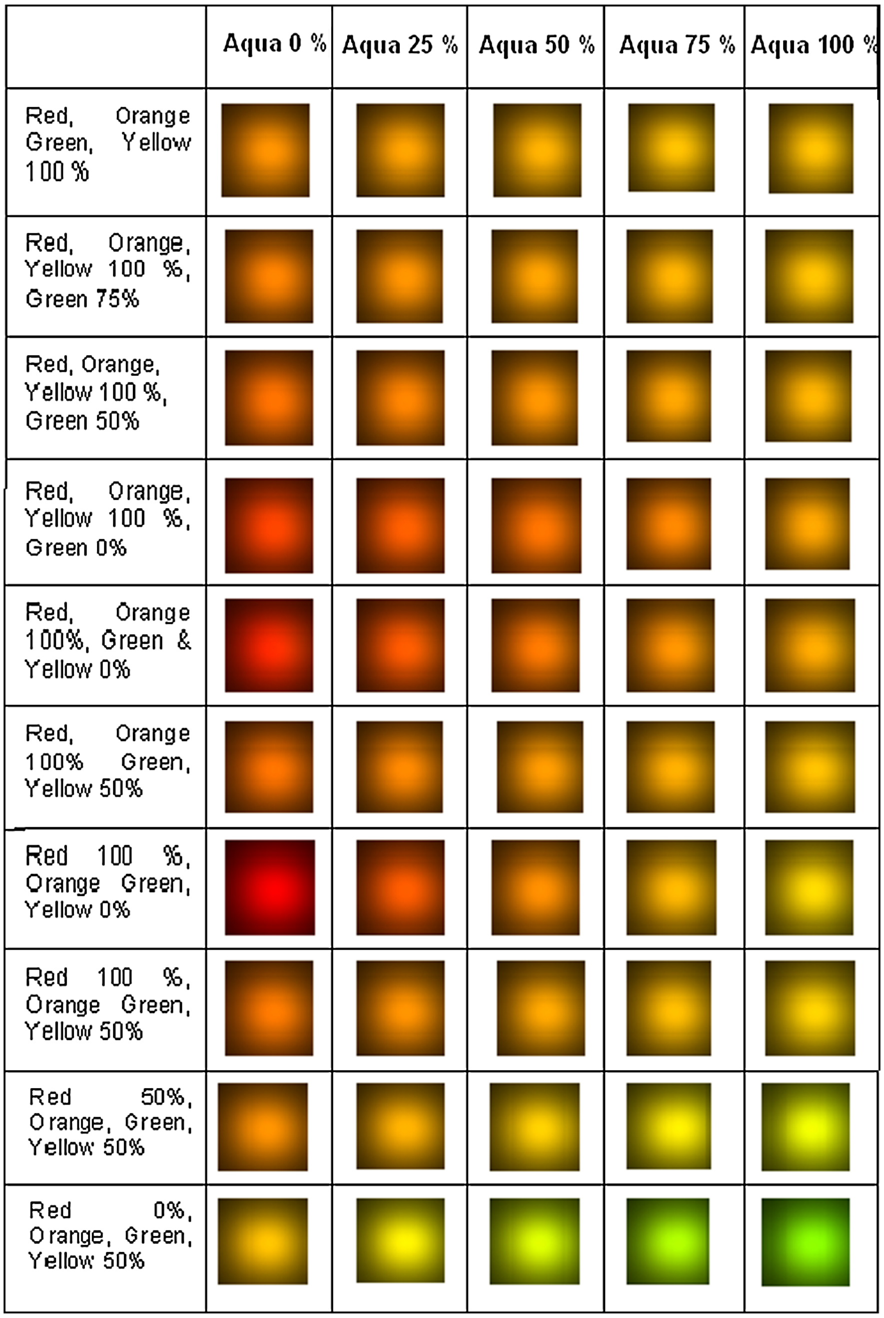


Fig. 8 Illumination patterns for various setting parameters of LEDs. (Color online only.)

4.1 *Illumination Performance*

The simulated results when all LEDs are 100% ON are given in Fig. 7.

Figure 7(a) gives numerical analyzed values of illumination system. The values show that the multielement LED source of 3 watt illuminates the target surface of dimension $320 \times 280\ \text{mm}^2$ with an average lux of 902. Maximum illuminance occurs at the center having value 1264 lux. Illuminance goes on decreasing at boundary side with minimum illuminance value as 274 lux. Using Eq. (1), the contrast ratio of illuminance on target surface is calculated. For the designed system, it is 0.64.

$$\text{Contrast Ratio} = \frac{\text{Illuminance}_{\text{max}} - \text{Illuminance}_{\text{min}}}{\text{Illuminance}_{\text{max}} + \text{Illuminance}_{\text{min}}}. \quad (1)$$

Uniformity of illumination is computed by OPTSIMLED, based on the equation:

$$\%\text{Uniformity} = \frac{\text{Average illuminance}}{\text{Maximum illuminance}} \times 100. \quad (2)$$

This value is 72.37%.

This uniformity metric does not consider spatial structure of illumination pattern for which human visual system (HVS) is quite sensitive. So further uniformity based on HVS, U_{HVS}, is computed using formula reported by Moreno et al.[20]:

$$U_{\text{HVS}} = \frac{100}{1 + k * \text{NU}^{\alpha} * \text{NU}_{\text{HVS}}^{\beta}}\%. \quad (3)$$

The values for k, α, and β are chosen to be 5, 1, and 0.5, respectively, as per the considerations in the paper.[20] Nonuniformity ‘NU’ is calculated as

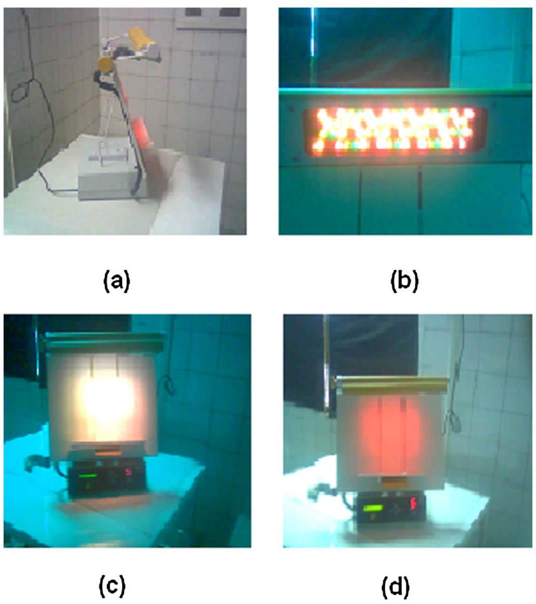


Fig. 9 Fabricated multielement illumination system photographs. (Color online only.)

$$\text{NU} = \frac{\sigma_E}{\bar{E}} = \left[\frac{1}{N-1}\sum_{i=1}^{N-1}\left(\frac{E_i - \bar{E}}{\bar{E}}\right)^2\right]^{0.5}, \quad (4)$$

where σ_E is standard deviation;

$\bar{E}$: average illuminance

E_i: illuminance at i’th pixel

U_{HVS} values are calculated for the designed source with normalized NU_{HVS} and vary between 34 to 62% for a range of NU_{HVS} of 0.1 to 1.0 and paper size $320 \times 280\ \text{mm}^2$. It is seen from gray-illuminance contours of Fig. 7(b) that the illuminance falls toward periphery smoothly. For A4 size paper, the uniformity, U_{HVS} improves to 65%. Those with low vision may have limited visual fields and for these smaller areas the uniformity is much improved.

The selection of LEDs is such that the spectral content of the individual light sources overlaps so that the net spectral content of the composite light source is close to that of warm white light. Figure 7(c) gives the illumination pattern of the fabricated system which is same as that of warm white light. The pattern shows uniform mixing of color and illuminance. No hot spots or dark spots are observed.

4.2 *Variable Illuminance and Color Illumination*

To produce the light of the desired color, the combination of color sources are switched ON and OFF. Different color shades and different illuminance level can be obtained by adjusting the current flowing through the individual LED. Simulation results of the specially designed luminaire are shown in Fig. 8.

It is possible to generate all color shades by adjusting the current through individual LED as shown in Fig. 8.

4.3 *Fabricated Light Source*

The photographs of the microcontroller based reading system are given in Fig. 9.

Figure 9(a) shows the reading system developed for individuals with Low Vision. Figure 9(b) shows the fully illuminated LED source, while Figs. 9(c) and 9(d) shows illuminated target plane when all LEDs are 100% ON and only red LEDs are 100% ON, respectively.

5 Conclusion

A universal illumination system with adjustable intensity and spectral output is designed using low power multielement LEDs and is simulated. The selection of the LEDs as the primary light source allows a far larger degree of flexibility in the construction and design of the composite light source than with the possible use of conventional light sources. Though the overall cost of the LED source is on the higher side as compared to conventional sources, it is further compensated by reliability and long life of sources. Moreover, in conventional sources, one has to use filter to change spectral contents of illumination. In the LED source system, spectral and illuminance control is simply achieved by changing current flowing through the individual LEDs. The reading system proposed is designed to be used by individuals. Any one individual may re-use the LED source without re-configuration by means of user identity.

Identification can be based on push button large enough in size and distinguishable by shapes and colors or by voice command or biometric identification.

Though concept of illuminance and color control using modulation of LEDs is developed for the reading purpose of individuals with low vision, the idea can be used for other similar applications.

Acknowledgments

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