Synthesis of pure white color and its equal power, equal chromatic splitting through a novel 3×3 fiber optic visible multiplexer

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Abstract: We report generation of pure-white color by mixing red, green, blue (RGB) lights from LEDs through a novel 3×3 fiber optics color synthesizer (FOCS), which is made of hard plastic cladding fiber (HPCF). The three output ports provided an equal power for the synthesized white color with almost identical CIE color coordinates. The FOCS rendered tunable white color temperature and optical properties of the outputs were experimentally investigated in terms of uniformity in power, photometric luminance, and color coordinate. We further packaged the device and applied to small form factor back light unit (BLU) to show feasibility in illumination uniformity enhancement.

OCIS codes: (060.2340) Fiber optics components; (230.1360) Beam splitters; (230.1150) All-optical device; (060.1810) Couplers, switches, and multiplexers; (330.0330) Vision and color

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#99177 - $15.00 USD Received 22 Jul 2008; revised 19 Sep 2008; accepted 22 Sep 2008; published 14 Oct 2008

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1. Introduction

High purity white color is being widely used in various areas of optical applications such as illumination [1], interferometry [2, 3], and displays [4,5]. In these applications, it is also of great importance to have capability to tune the color temperature, which will endow a new degree of freedom to design the optical system maximizing human vision adaptability. In display applications, the color gamut would be determined by the emission spectrum of the light source as well as the transmission spectra of the color filters in a color illumination system such as back light unit (BLU) of liquid crystal displays (LCDs). The color temperature can be consequently adjustable from rending R,G and B luminance of these illumination systems [4]. Optical fiber compatible white color source would fit well to recent micro-optic or nano-optic technologies, where spatially localized sources are required. Despite highly sophisticated technological achievements in fiber optic devices in IR optical communication applications, only a few attempts have been reported in the visible range devices especially for color rendering. Fiberized tunable white color source and fiber optic devices in the visible range would contribute to fulfill immediate future needs in optical technologies in various emerging areas. Recently a novel fiber optic color synthesizer (FOCS) has been reported based on 1×3 hard plastic cladding fiber (HPCF) coupler along with solid state RGB LEDs by one of the authors, which could serve as a micro scanning display color source [6].

In this study, we further developed the fiber optic fused taper technology from one output port device 1×3 fiber multiplexer [6] into three output port 3×3 fiber optic color synthesizer to realize a unique microscopic tunable white color source transforming red, green, blue (RGB) inputs into three white color outputs of the same color coordinate and equal power, which has not been achieved previously. In three outputs of the proposed device, tunability in white color temperature along with excellent uniformity in terms of both chromaticity and optical power splitting ratio was achieved for the first time to the best knowledge of the authors. By applying the proposed device to BLU system, detailed optical properties such as color gamut and illumination characteristics were investigated for the first time. At the same time, colorimetric applications were discussed by exploring the tuning ability in the correlated color temperature. This preliminary result of fiber optic application in the visible applications could open a new door of visible fiber optics, which has not been intensively attempted.

2. Theory

The fibers used in the experiments were provided by Luvantix$^{\text{TM}}$ and they are composed of 200μm pure silica core along with 15μm thick low index polymer cladding. Typical numerical aperture ranges from 0.37 to 0.48. Due to large core and high refractive index contrast, HPCF holds numerous guiding modes and the guiding properties can be well approximated by the scalar wave equation [7, 8]. The scalar wave equation for the electric field distributions E of the uniform waist region of a twisted coupler is

$$\frac{\partial^2 E}{\partial x^2}+\frac{\partial^2 E}{\partial y^2}+(k^2 n_0^2-\beta^2)E+\frac{(x^2+y^2)\beta^2}{h^2 b^2}E+\frac{1}{h^2 b^2}\left(x\frac{\partial}{\partial x}+y\frac{\partial}{\partial y}\right)E=0 \qquad (1)$$

where $2\pi b$ is the twist pitch, $h^2=\frac{x^2}{b^2}+\frac{y^2}{b^2}+1$, n_0 is the refractive index distribution, β is the propagation constant of the mode E, and $k=2\pi/\lambda$ [7,8].

#99177 - $15.00 USD Received 22 Jul 2008; revised 19 Sep 2008; accepted 22 Sep 2008; published 14 Oct 2008

Two approximations can simplify Eq. (1). One is that the twist pitch $2\pi b$ is long enough compared with the width of the coupler. Hence, $h^2 \approx 1$. The other is the factor β^2 in Eq. (1) can be replaced by $k^2 n_0^2$, since most of the light wave propagates in regions where $n_0 \approx \beta / k$.

The last term in Eq. (1) could be neglected with the same approximation. The magnitudes of last two terms can be expressed by $(x^2 + y^2) k^2 n_0^2 |E| / b^2 \approx V^2 |E| / b^2$ and $U |E| / b^2$, respectively. Here V is the normalized frequency and U is the transverse wavenumber in the core as defined in optical waveguide theories. Since the last term is a product of U $\approx \sqrt{(k^2 n_0^2 - \beta^2)}$ and $|E| / b^2$ this can be neglected, for case of $V^2 >>$ U far from cutoff [9].

Thus, the simplified wave equation is

$$\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + (k^2 n_{eff}^2 - \beta^2) E = 0 \tag{2}$$

where

$$n_{eff}^2 = \left[1 + \frac{(x^2 + y^2)}{b^2} \right] n_0^2 \tag{3}$$

is an effective refractive index induced in the coupler waist region by a twist of pitch $2\pi b$ [9,10].

From Eq. (3), the twisting of a fused tapered coupler excites the change in the effective refractive index, which increases quadratically with the distance from the coupler axis. It causes a redistribution of the modal fields in the coupler away from the longitudinal axis which makes field overlap among coupling modes.

In this study, we also adopted twisted taper coupler to efficiently mix the R,G,B colors along the fused taper. Detailed theoretical analysis of the color mixing has been theoretically investigated elsewhere [11,12], which is beyond the scope of this paper and we will concentrate on discussion for experimental optimization in the HPCF couplers in terms of color mixing and its output distribution through the tapered coupling zone.

3. Device fabrication

The schematic diagram of the proposed device is shown in Fig. 1. Two main components of the device are; a specially fabricated of 3×3 HPCF coupler, and fiber pigtailed RGB LED packages. The RGB colors are propagating individually along the three input HPCFs, exciting multitude of guided modes. The modes carrying RGB colors subsequently coupled one another as they enter the fused taper, to generate white color at an appropriate mixing process at optimal tapering conditions. Once the pure white is obtained in the tapered mode coupling region, the white color further propagates along the taper and then splits into three outputs. The HPCF coupler was specially fabricated for visible range operation and highly efficient color mixing of RGB primaries along the fused taper was successfully achieved. The fused taper region was further optimized so that the three outputs could maintain the same chromaticity of the mixed color with the identical optical power level. The proposed device is, therefore, playing a unique role of wavelength division multiplexer and equal power splitter, simultaneously in the visible RGB spectral domain. It is the first visible range fiber optic device, to the best knowledge of the authors, which transforms RGB inputs into three

#99177 - $15.00 USD Received 22 Jul 2008; revised 19 Sep 2008; accepted 22 Sep 2008; published 14 Oct 2008

outputs with identical power level, chromaticity, and color temperature in the pure white color range.

For fabrication of the special 3×3 HPCF coupler, we adapted the fusion-tapering technique using micro-flame brush [13,14]. In order to accommodate large silica core diameter of HPCF, tapering zone parameters such as flame temperature, elongation length and waist width were experimentally optimized for low loss and high uniformity among output powers, by in-situ monitoring of the outputs using an optical spectrum analyzer (OSA). For efficient color mixing, we found that the elongation length of 15.5mm and, the waist width of 130μm were optimal for the RGB LEDs used in the experiments, which were provided by Kopin^{TM}. Note that the device can realize a small form factor of 0.30mm×1.0mm×15.0mm volume that can endow significant advantages over conventional bulk optics using lenses and thin film filters for micro-illumination and display systems.

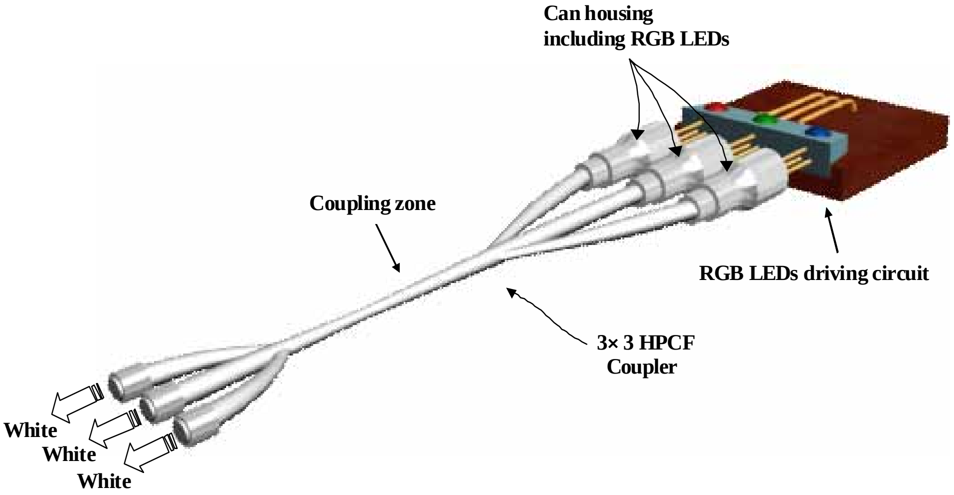


Fig. 1. Schematic diagram of the fiber-optic red, green, blue to three whites color splitter.

The HPCF, provided by SSCP^{TM}, had a core diameter of 200μm and a polymer clad thickness of 15μm. The fiber showed a numerical aperture of 0.38, and its core and clad had the refractive index of 1.45 and 1.4, respectively, as depicted in the inlet of Fig. 2. Since the diameter and numerical aperture of HPCF is large enough to accept the light from LED, we adopted butt-coupling method with an optimal gap to launch the lights from RGB LEDs to HPCF input ports. The three input fibers of the device were pigtailed and packaged individually with RGB LEDs as schematically shown in Fig. 2. The package consists of a ferruled fiber, ferrule housing, can housing and a TO-caned LED. A ceramic ferrule for the HPCF was fabricated by Shin Han Photonics incorporated, which was inserted into the ferrule housing. After proper alignment procedures, a laser spot-welding was applied into the package as denoted in the dark spots in Fig. 2. We used the hermetic laser-weld sealing method [15], which can provide high mechanical and environmental reliability. In order to optimize the HPCF-LED distance, and subsequently to increase the coupling efficiency, we modified the bonding sequence such that firstly ball bonding was applied on the TO46 stem and secondly the wedge bonding on the pad of LED chip was applied. In the LED driving electronics, the power level of RGB lights were controlled by an 8-bit digital to analog converter (DAC) independently. By individually controlling the power of RGB and subsequent color mixing the fused taper, we realized the pure white light from the three outputs of the 3×3 HPCF coupler.

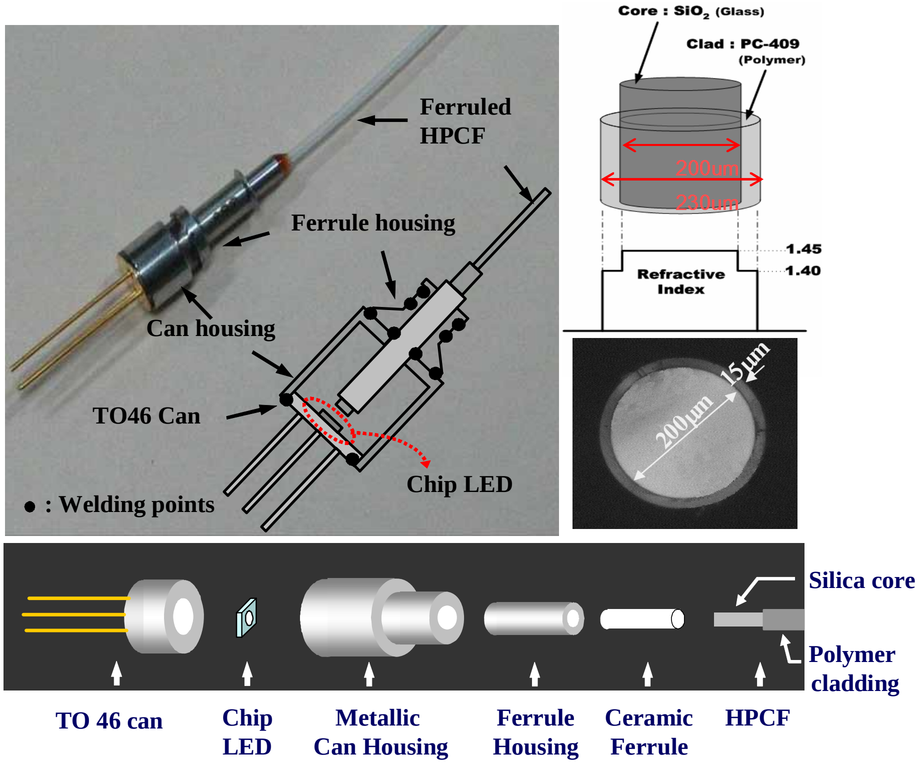


Fig. 2. Schematic diagram showing the components for LED and HPCF input port package. Refractive index diagram and the dimensions of the used HPCF are shown in top-right.

4. Experiments and results

Optical properties of the device were investigated in terms of output power splitting ratio, chromaticity, and color temperature along with their uniformity among the output ports. In order to characterize the splitting ratio in the visible range, the pristine 3×3 fused taper coupler without LED pigtail was firstly tested. A light source from a tungsten-halogen lamp was launched into one of three input ends and the transmission from each of three outputs was measured by an OSA. The insertion loss spectra for three outputs are summarized in Fig. 3. It is noted that the insertion loss in the range of 600 to 700nm showed a very uniform value about 5.5 dB with a low excess loss of 0.8dB. The device provided uniform optical power splitting ratio such that optical power was evenly split by 1/3 among the output ports. Over the spectral range, the output variation ratio was less than 0.3 dB. We did similar experiments using an optical power meter and RGB LEDs individually and confirmed the same uniformity in the insertion loss and splitting ratio.

For the TO can type packaging in Fig. 2, the coupling loss from RGB LEDs to the HPCF input ports was measured to be about 8.25 dB, 10.86 dB, 11.72 dB, respectively. By varying RGB power ratio, white light was generated in the fused taper coupling region, which further guided through three output ports. Typical spectrum of the synthesized white color from the device output port measured by a commercial optical spectrum analyzer (OSA) is shown in Fig. 4, where the relative optical power ratio of the R,G,B can be inferred. The RGB LEDs had the peak brightness of 279, 338, 100mcd near the wavelength of 635nm, 529.9nm, 442.7nm, respectively. The view angles were 135.2°, 148.9°, and 146.9° for the red, green, and blue LED, respectively.

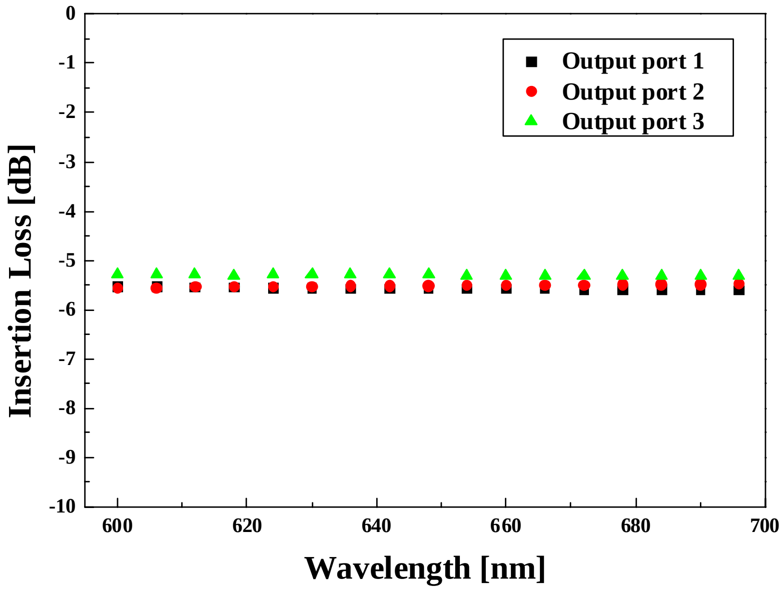


Fig. 3. The uniformity in the insertion loss and power splitting ratio among the three output of the proposed device.

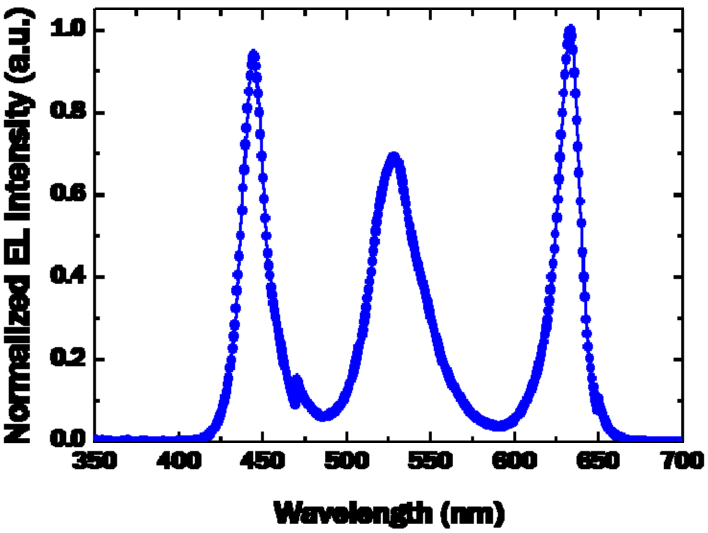


Fig. 4. Typical Spectrum of white color output synthesized by the proposed device.

For the packaged device as shown in Fig. 1 and Fig. 2, photometric measurements were carried out using a standard colorimeter (Minolta Chroma meter CS-100A). The luminance of red, green, and blue light at the three output ports was measured maintaining the same LED driving current of 20mA. In the luminance measurements one of RGB LEDs was turned on while turning off the other two colors. The results are summarized in Table 1 for R,G,B, and white color. As in the case of power splitting in Fig. 3, we could confirm that luminance was also equally divided among three outputs. By controlling each power level of RGB LEDs with the 8 bit digital to analog converter, we realized the white color from all of three output

#99177 - $15.00 USD Received 22 Jul 2008; revised 19 Sep 2008; accepted 22 Sep 2008; published 14 Oct 2008

ports, whose photometric brightness was in the range of 10062~10094 cd/m^2. Very small deviation of less than 0.3% in the brightness of the white color among the outputs clearly confirms the uniformity of the device in the luminance and optical power. We also measured the color coordinate of synthesized white lights from the proposed device. Figure 5 shows the CIE 1931 Chromaticity Diagram of the three outputs. The color coordinates of white light outputs were ($x=0.2918$, $y=0.3084$), ($x=0.2972$, $y=0.3063$), and ($x=0.2962$, $y=0.3075$) for output port 1, 2, and 3, respectively. We could confirm that the device provided an excellent uniformity in the chromaticity around the pure white zone.

Table. 1. The luminance of red, green, blue, and mixed white from output ports of the proposed 3×3 HPCF coupler

	Port1 Luminance (cd/m^2)	**Port2 Luminance (cd/m^2)**	**Port3 Luminance (cd/m^2)**	**Total Luminance (cd/m^2)**	**Average Luminance (cd/m^2)**	**Standard deviation**
Red	**6250**	**6258**	**6249**	**18757**	**6252**	**5.07**
Green	**5501**	**5509**	**5495**	**16505**	**5502**	**5.74**
Blue	**495**	**499**	**486**	**1480**	**493**	**5.45**
White	**10078**	**10094**	**10062**	**30234**	**10078**	**13.06**

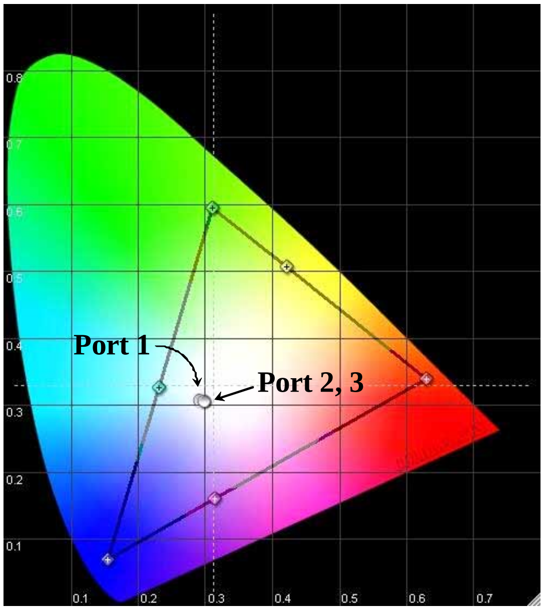


Fig. 5. The CIE 1931 Chromaticity Diagram of white colors from three outputs of the proposed fiber-optic white color synthesizer.

In terms of color purity of synthesized white, the proposed device showed good performances equivalent to conventional bulk optic color synthesizer leaving no observable traces of R,G,B inputs on the CIE diagram. Commercial bulk optic color synthesizers are using dichroic mirrors that have limited bandwidths both in reflection and transmission. Overall throughput of the bulk optic color synthesizer, therefore, is restricted within the

#99177 - $15.00 USD Received 22 Jul 2008; revised 19 Sep 2008; accepted 22 Sep 2008; published 14 Oct 2008

bandwidth of the dichroic components. In contrast, the proposed fiber optic device synthesizes the output color by the mode coupling within the coupling zone of the fused taper, which is inherently broad band over several hundred nanometers for multimode fibers such as HPCF used in the experiments. Therefore the proposed device can show better color tunability with a wider color gamut area than conventional bulk optic devices.

We further explored the tuning ability of the proposed device in correlated color temperature of the synthesized white color. The correlated color temperature of a light source is determined by a standard procedure, comparing its chromaticity with a theoretical black-body radiator. Theoretical black-body radiation is determined by Plank's law and it is denoted as a black curve in the CIE diagram as in Fig. 6. The temperature at which the heated black-body radiator matches the color of the light source is that source's correlated color temperature [16, 17]. Among various tones of white colors, there are important standard whites with specific correlated color temperatures, D50 (5000 K), D55 (5500 K), D65 (6500 K), and D75 (7500 K). In color monitor, video, and digital cameras, the white color is referenced to D65 whose correlated color temperature is 6500K. Using the proposed device, we could tune the correlated color temperature of the three outputs and the results are shown in Fig. 6. Correlated color temperatures of 5000K to 7500K were continuously achieved including D65 standard. We could confirm unique correlated color temperature uniformity among the three outputs of the device.

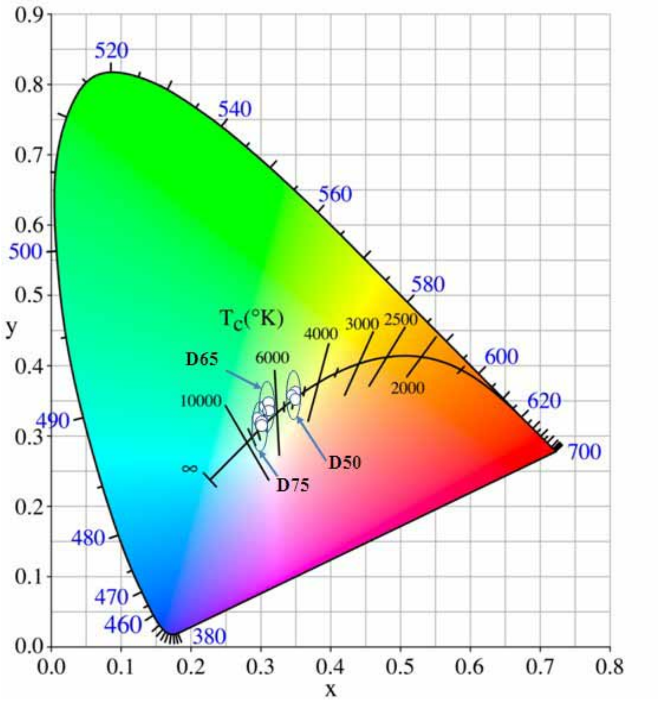


Fig. 6. Theoretical black-body radiation determined by Plank's law (in black line) and the correlated color temperature distribution 5000 K (D50), 5500 K (D55), 6500 K (D65), 7500 K (D75) of the three outputs from the proposed device.

Using this white color synthesizer with high uniformity among each port, we adapted the three white outputs to a 0.44 inch BLU that consists of a lightguide plate, a diffuser sheet, and two prism sheets, provided by Kopin^{TM}. In the small size LCD displays using LED backlight systems, non uniform spatial distribution of LED results in the issue of dead zone. FOCS can provide multiple white outputs which can be arrayed along the light guide plate to provide a better uniformity in BLU illumination characteristics along with an optimized diffraction pattern within the light guiding plate.

In comparison to conventional white LED or RGB LEDs, the FOCS can provide three fiber outputs with identical power, chromaticity, luminance, and correlated color temperature, which can make flexible arrangements for BLU homogenization. The uniformity in luminance distribution was measured by varying parameters such as the distance (D) between the BLU and fiber outputs, and the spacing (S) between fiber outputs as shown in Fig. 7(a). The luminance distribution characteristics on the backlight were measured by using a PC-interfaced colorimeter. The luminance distribution plane is corresponding to the 0.44 inch BLU plane. After selecting 25 points within the constructed luminance distribution plain, we extracted luminance uniformity which is defined as;

$$\text{Luminance Uniformity} = \frac{\text{Minimum Luminiance among 25 points}}{\text{Maximum Luminiance among 25 points}} \tag{4}$$

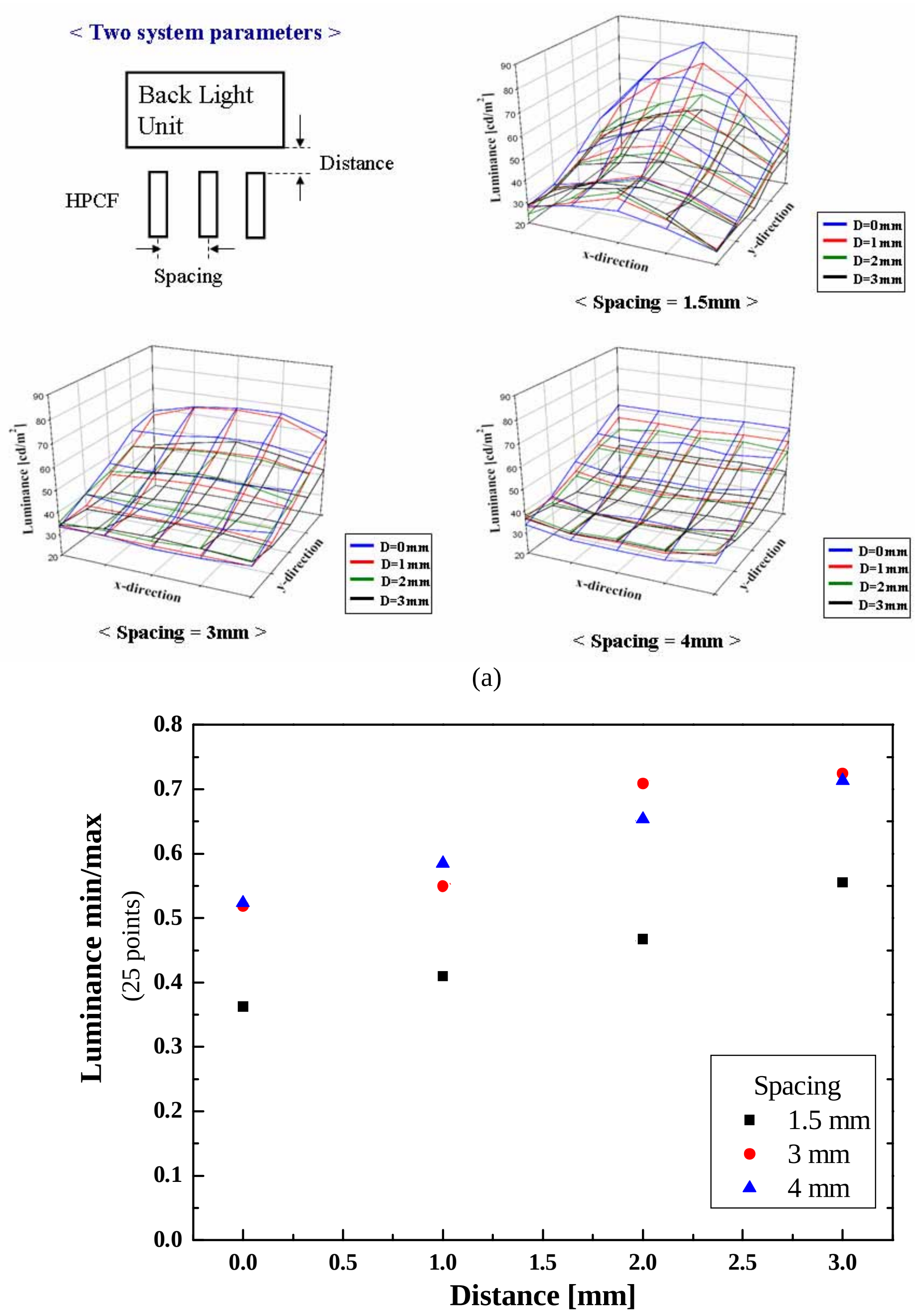
The highest luminance in the case of a distance (D) of 0mm and spacing (S) of 1.5mm was 87.6 Cd/m2 and the luminance uniformity was 36.27%. In the distance (D) of 3mm and the spacing (S) of 3mm, the uniformity reaches 72.29% with the peak luminance of 52.36 Cd/m2. Figure 7(b) represents the luminance uniformity profile as a function of distance (D) and space (S) based on Eq. (4). The uniformity is significantly increased in comparison to conventional single white LED illumination case (average uniformity less than 62%) and further upscaling to a larger BLU is being investigated by the authors.

5. Conclusion

We realized a novel three port fiber-optic RGB to white color synthesizer using a unique 3×3 HPCF fused taper multiplexer along with HPCF-pigtailed RGB LED packages. The device combines two device principles wavelength division multiplexer for RGB and equal power splitter, converting RGB colors from LEDs into three identical white color outputs. The device had a low insertion loss less than 5.5 dB, along with the excess loss of about 0.8 dB. Excellent uniformity among the outputs of the device has been achieved in four natures; 1) optical power splitting among output ports, 2) photometric brightness of three white light outputs, and 3) color coordinates of outputs on the CIE gamut, and 4) Correlated color temperature of the outputs. We also implemented the device in a commercially available 0.44 inch BLU system and obtained a significantly improved uniformity in luminance distribution by using the three white light outputs of the proposed device.

Acknowledgments

This work was supported in part by the KOSEF (Program Nos. ROA-2008-000-20054-0, R01-2006-000-11277-0, and R15-2004-024-00000-0), and in part by the KICOS (Program Nos.2007-8-0536, 2007-8-1864, and 2007-8-1867), the ITEP (Program No.2007-8-2074), and the Brain Korea 21 Project of the Ministry of Education and Science



(a)

(b)

Fig. 7. The luminance distribution characteristics of the backlight utilizing the proposed device: (a) the luminance distribution as a function of the distance (D) and space (S), (b) The luminance profile of the backlight

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