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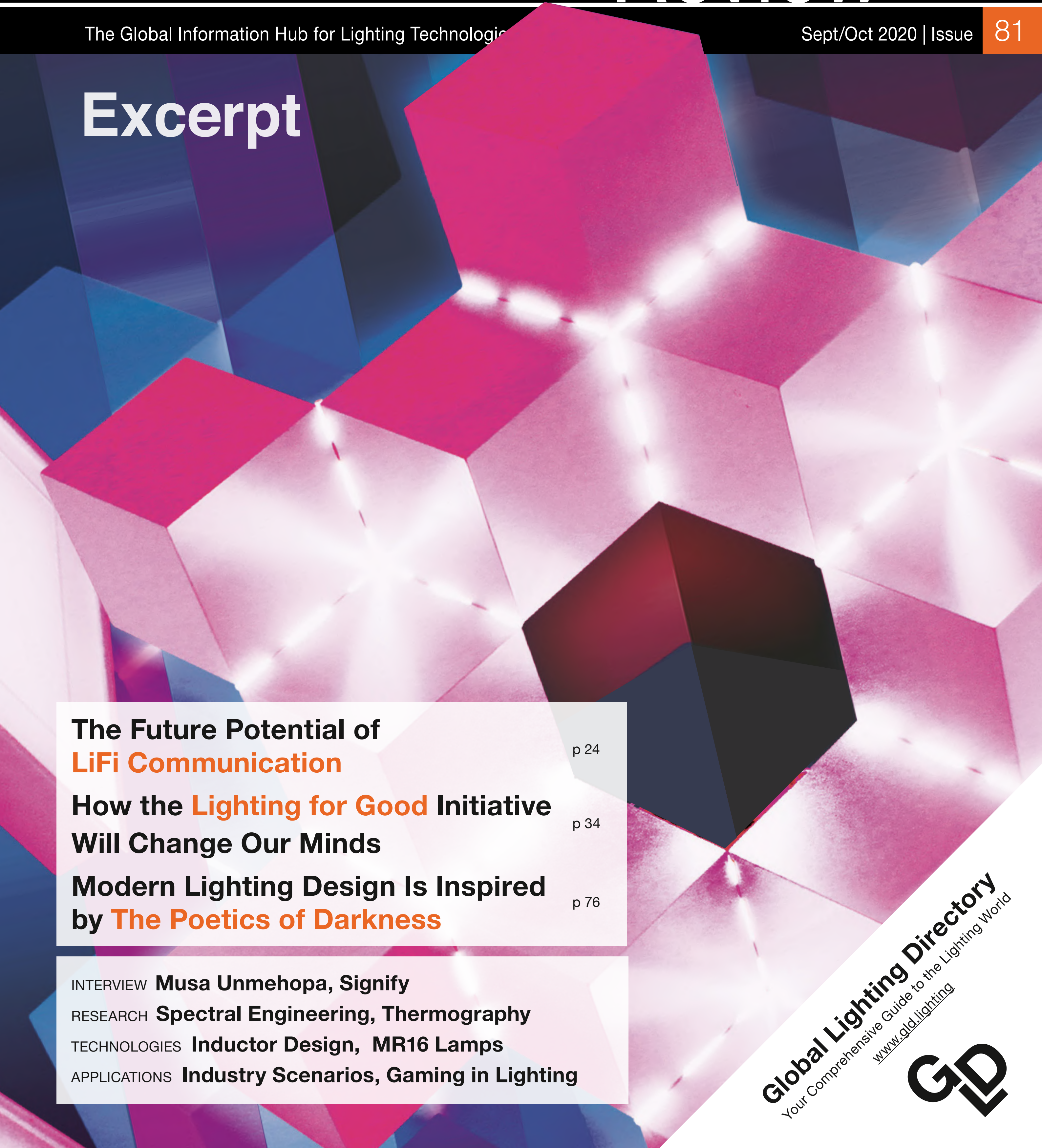


Excerpt

The Future Potential of LiFi Communication p 24

How the Lighting for Good Initiative Will Change Our Minds p 34

Modern Lighting Design Is Inspired by The Poetics of Darkness p 76

INTERVIEW **Musa Unmehopa, Signify**

RESEARCH **Spectral Engineering, Thermography**

TECHNOLOGIES **Inductor Design, MR16 Lamps**

APPLICATIONS **Industry Scenarios, Gaming in Lighting**

Global Lighting Directory
Your Comprehensive Guide to the Lighting World
www.gld.lighting
GLD

4 EDITORIAL

COMMENTARY

8 Visual Performance and Cognition
by Stephen A. MASON, Dr., Founder and Head of Sustainable Eye Health, Australia

NEWS

10 International Lighting News
21 Regulation News

LpS DIGITAL

22 LpS Digital – Conference & Exhibition

LpS DIGITAL
CONFERENCE

The Role of Standards
In Harnessing Luminaire Data

What Makes D4i and Bluetooth® Mesh a Perfect Couple for IoT Data Monetization?

Szymon SLUPIK, CTO at Silvair, Poland
Chair of the Bluetooth Mesh Working Group at Bluetooth SIG

L200819-Wireless-Communication

INTERVIEW – LIFI COMMUNICATION

24 Musa UNMEHOPA, Head of Ecosystems and Strategic Alliances for LiFi at Signify
compiled by Arno GRABHER-MEYER, LED professional

LIFI PATENTS

30 Thrust Area Analysis of LiFi Communication Patents
by Günther SEJKORA, Dr., R&I Manager at Luger Research | CEO of Items

CIRCULAR ECONOMY

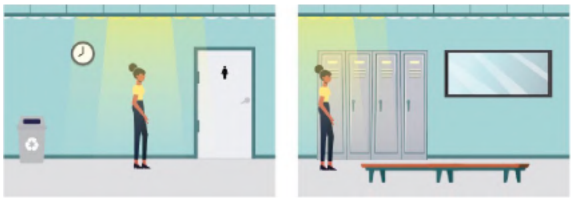
34 Lighting for Good
by Nicolas MARTIN & Tiphaine TREINS, Lighting Manager at LVMH & Founder and Principal of Temeloy Advanced Lighting Design

ECODESIGN AND ENERGY LABELLING

38 New Requirements for Energy Efficiency and Labelling of Lighting
by Fabian FLIGGE, Product Expert at TÜV SÜD

LIGHTING INDUSTRY SCENARIOS

40 Future Scenarios of the Lighting Industry: Towards a More Sustainable and Innovative Market
by Ganix LASA, Ph.D., Professor at the Mondragon University, Spain



LED STUDY

46 Full Spectrum LED Study 1.0
by Daniel NEVES PIMENTA, Arch. & Lisa-Marie WADLE, M.Sc., Project Engineer & Researcher at Fraunhofer IBP

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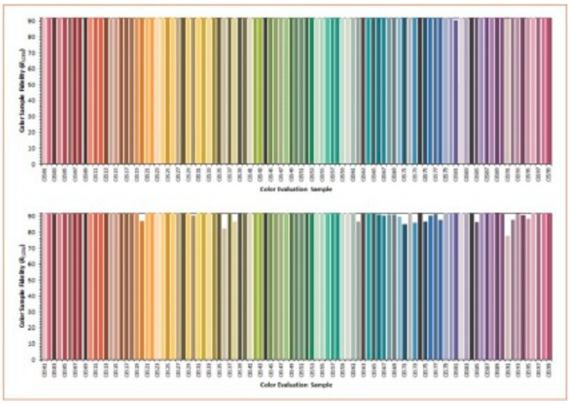
AVERAGE SPECTRAL DIFFERENCE

52 Average Spectral Difference – New Metric to Evaluate the Naturalness of Artificial Light Sources
by Brian CUMPSTON, Dr., VP of Solutions Development at Bridgelux



SPECTRAL ENGINEERING

58 Facing the Challenges of Spectral Engineering with a New Software Tool
by Adrià HUGUET-FERRAN, Ph.D. Candidate at University of Barcelona | CTO at Kumux

THERMOGRAPHY OF LED MODULES

64 Transient Infrared Thermography for Thermal Conduction Path Analysis of LED Modules
by Peter W. NOLTE, Dr., Research Team Leader at Fraunhofer Application Center for Inorganic Phosphors

AUTOMOTIVE LIGHTING

68 Choosing the Right Inductor Technologies for Automotive LED Lighting
by Bill GISSELER, Senior Applications Engineer at TDK Corporation of America

LED LAMP MR16

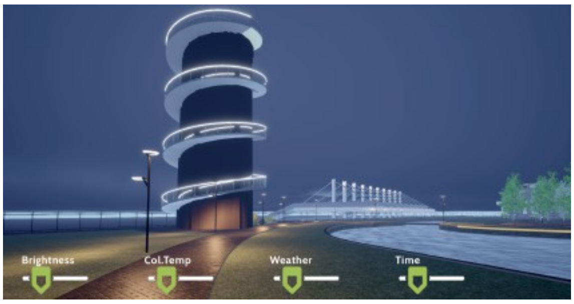
72 Combination of an Advanced Thermo-Transfer Technology and a Novel High Impact Light Source to Improve MR16 Products
by Bertrand OUELLET, Founder and Owner of LUBO Lighting

LIGHTING DESIGN I

76 The Poetics of Darkness
by Monica LLAMAS & Florencia CASTRO, both of MFA Lighting Design, B.A. of Architecture

LIGHTING DESIGN II

82 Gaming in the Lighting Sector – A Game Changer?
by Wolfgang BERNECKER, Founder and CEO of FutureACT



86 ABOUT | IMPRINT

ADVERTISING INDEX

1 Global Lighting Directory
2 Instrument Systems
3 Cree
5 Röhm
9 Seoul Semiconductor
11 Trends in Lighting
13 World Architects
15 Toplite
17 GL Optic
19 Simpex
31 Nordic Power Converters
33 Luminus Devices
44 Repro-Light
45 LightingEurope
55 Bridgelux
57 Global Lighting Directory
63 LpR Submissions
67 LpS Digital
71 European Photonics Industry Consortium
75 Sustainable Eye Health
87 LED professional Review
88 LpS Digital

Average Spectral Difference – New Metric to Evaluate the Naturalness of Artificial Light Sources

Lighting has more effect on people than just enabling us to see – it can also impact and affect our mood and health. Advanced spectral engineering methodologies enable spectral manipulation to enhance or reduce emission at specific wavelengths. This technology can be used to augment or suppress specific targeted wavelengths in the emission spectra, or to reduce spectral spikes and valleys to improve the spectral consistency to that of natural light, both of which may affect human physiology. While there are differing schools of thought in the lighting industry, delivering natural light is of primary interest to many human centric lighting advocates. This raises the question: how do we objectively quantify naturalness? Standard lighting quality metrics such as CRI and TM-30 do not fully address this naturalness question. This article presents a new metric, Average Spectral Difference (ASD), which provides a quantitative measurement of how closely a light source matches the spectra of natural light.

Characteristics of Natural Light Sources

In recent years, the lighting industry has begun to explore ways to improve the quality, as much as the quantity, of light produced by LED light sources. More broadly, lighting designers, specifiers, and end-users are exploring the concept of human-centric lighting (HCL). HCL has many definitions, but it is broadly agreed that it encompasses the effects of lighting on the physical and emotional health and well-being of people.

While there are many factors that can be considered in developing a human centric light source such as color temperature, color rendering, glare, flicker, and more, the spectral power distribution (SPD) of the source is a fundamentally important factor to consider. There are two main areas of research and development for spectral enhancement of LEDs tailored for use in HCL applications: exaggeration or naturalness.

The first area focuses on influencing human behavior. Several studies have shown that enhancing or retarding certain wavelengths can affect human physiology. Through increasing intensity in the blue to cyan wavelength ranges, melatonin secretion can be suppressed, increasing alertness. Conversely, through reducing emission in these wavelength ranges, the opposite effect can be achieved, increasing restfulness and relaxation. While various scientific studies have been conducted to support this interaction with light at specific wavelengths and human physiology, the long-term effects of this artificial influence on humans remains unknown.

The second area focuses on replicating the spectra of natural light, under which humans have evolved for hundreds of thousands of years. There is a strong presumption among lighting experts and HCL advocates that the more natural a light source is, the better for the observer. Mimicking the spectra of natural light sources offers advantages in bringing natural lighting to interior environments where humans spend most of their time, and lighting specifiers for both residential and commercial spaces such as offices, schools, care homes, and hospitals might also presume that the safest option is to avoid exposing people to non-natural augmented lighting.

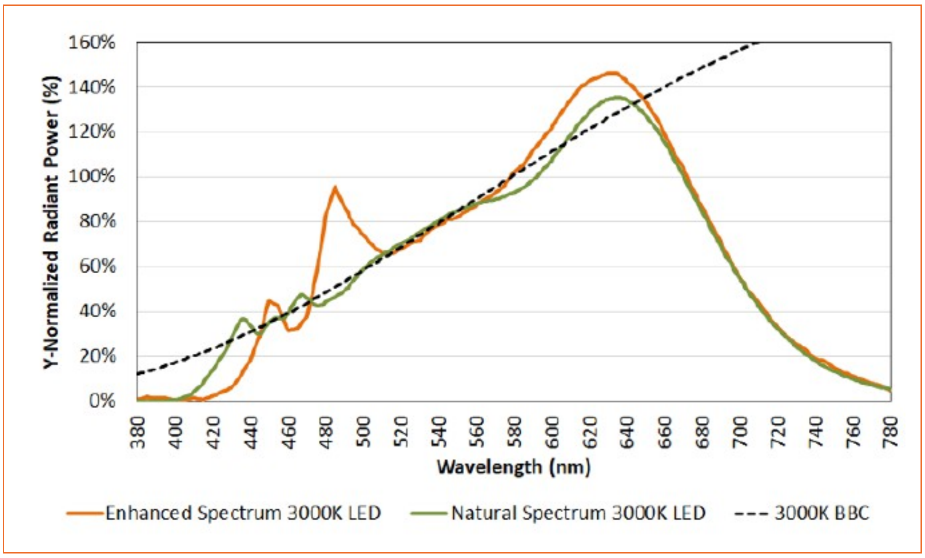


Figure 1: Spectral engineering examples of 3000 K LEDs targeted for human centric lighting

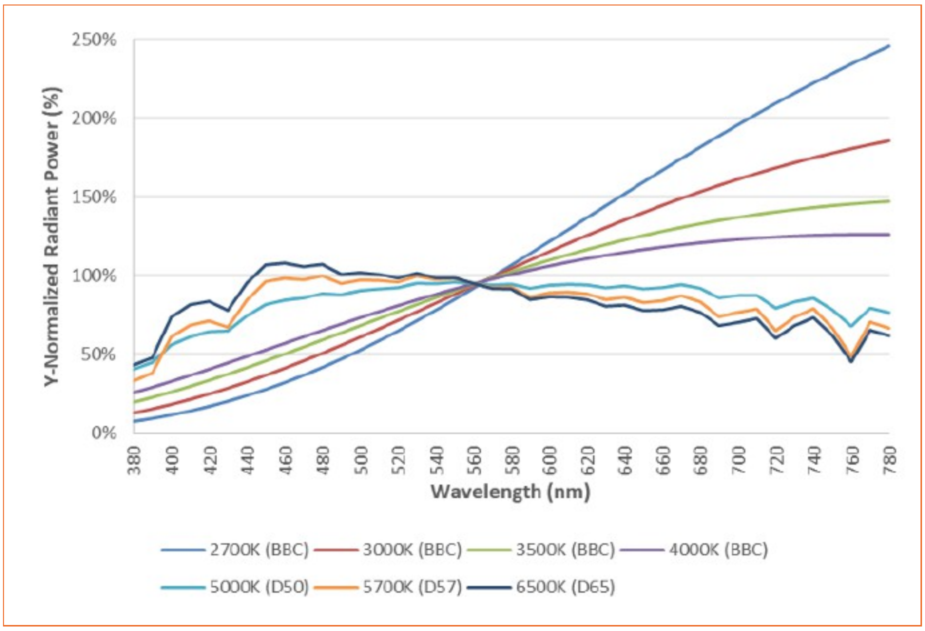


Figure 2: The standardized reference SPDs of natural light

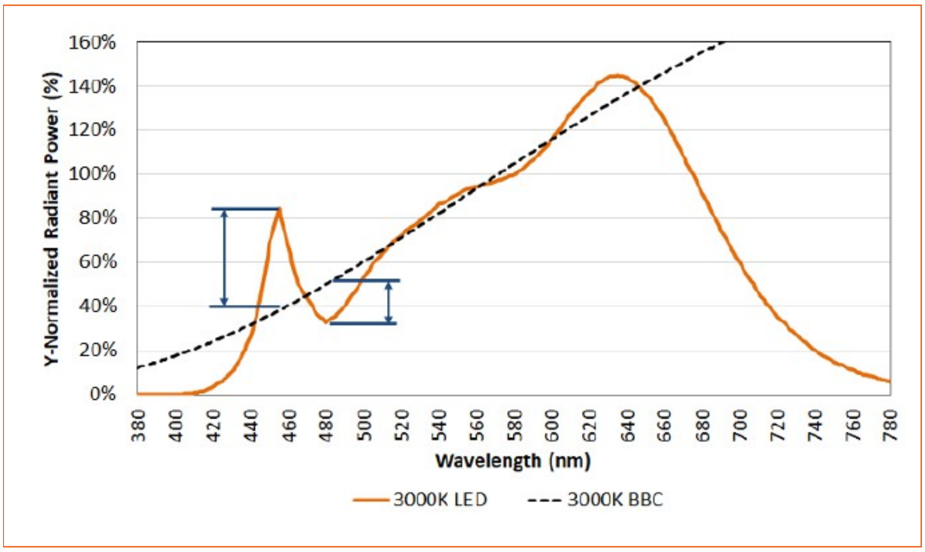


Figure 3: SPD of a typical 98 CRI 3000 K LED with IES TM-30 R_f of 94 and R_g of 102, still exhibiting a spectral spike at 450 nm and valley at 480 nm

Figure 1 shows spectral power distribution curves for two 3000 K LED light sources against the 3000 K Black Body Curve (BBC). The enhanced spectrum pertains to the first area of R&D where the SPD is selectively exaggerated to nudge human physiology into a “wakefulness” state, whereas the natural light SPD is indicative of the second area of R&D in which the spectrum is engineered to match natural light. By looking at these SPDs, we can qualitatively see that the natural light curve matches the BBC much more closely than the enhanced spectrum curve, however arriving at a quantitative comparison has eluded industry experts, until now.

Evolution has conditioned humans to function in daylight hours by the light of the sun, and after dusk, in the warm glow of fire. Thus, we define natural light sources as those of sunlight and firelight. Conveniently, these natural light sources have standardized spectral definitions, ubiquitous in the lighting industry. The most widely used scientific method for defining a light source is the SPD, typically plotted on a graph of the type shown in **Figure 1**.

Likewise, **Figure 2** plots the standardized spectral definitions of natural light. They represent the exact balance of wavelengths to which evolution has conditioned the human body to respond, and under which humans have evolved and thrived.

SPDs can be plotted for any visible light source. If an artificial light source with a color temperature of 6500 K, for example, has a spectral power distribution closely matching the D65 curve in **Figure 2**, it will have a higher Color Rendering Index (CRI) value compared to a light source that does not match the standardized spectral reference as closely.

Color quality metrics such as CRI and TM-30 provide important information about the extent to which a light source matches the lighting effect of a natural reference source such as daylight (at cooler color temperatures of $\geq$5000 K) or the black body curve (at warmer color temperatures of $\leq$4000 K). However, two different light sources with the similar CRI, TM-30 R_f, and TM-30 R_g values may appear differently when viewed side by side, or may have vastly different physiological impacts, because they have significantly different SPDs. Thus, these metrics alone are insufficient to define the naturalness of light. **Figure 3** compares a 3000 K LED with near perfect CRI of 98, to the standardized definition of a 3000 K natural light source (i.e. the black body curve). The comparison shows that simply having high CRI and TM-30 values does not necessarily mean that the source is a close match to the spectra of natural light, as indicated by the highlighted spectral peak and valley.

Average Spectral Difference: A Definitive Measure of Naturalness

To quantify the relative difference in naturalness between SPDs, we must first consider the spectral range in which the comparison is made. Although the spectral range of human vision stretches from 380 nm to 780 nm, the subset of this range that corresponds to the photopic response curve, or V(λ), is ideal for this calculation. V(λ) is the luminous efficiency function describing the average spectral sensitivity of human visual perception of brightness. The wavelength range of 425 nm to 690 nm was chosen to remove the tails of the V(λ) gaussian distribution below 1% of the peak value at 555 nm. While the V(λ) curve stretches from 380 nm to 780 nm, the rationale for reducing the total range is rooted in maximizing the usefulness of the comparison between light sources. As the ASD acronym reads, the metric uses an "average" of the spectral differences between two SPDs across a range of spectra. Since nearly all LED light sources have low emission at the low and high ends of the visible spectrum, averaging the spectral differences over the entire range results in a less meaningful comparison as the data is skewed by the lack of emission at the tails of the distribution. The range proposed covers 99.9% of the total area under the photopic response curve, shown in **Figure 4**.

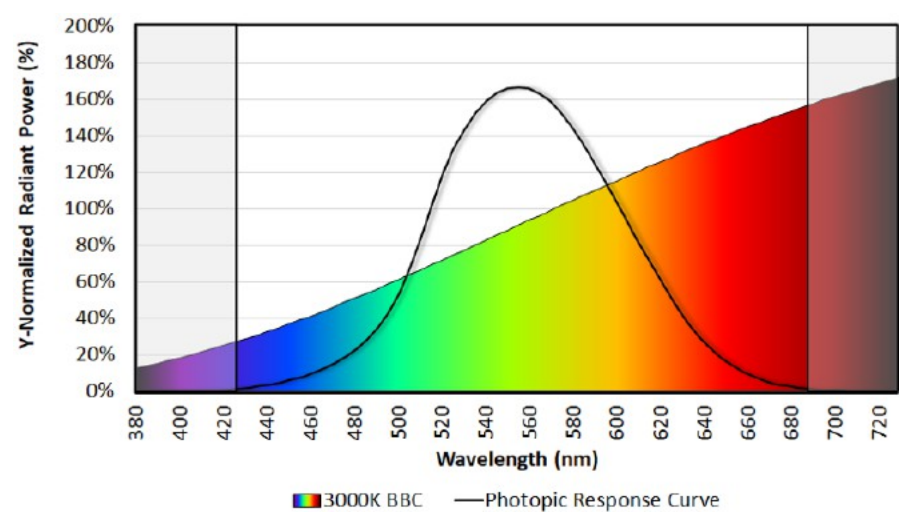


Figure 4: Photopic response curve, V(λ), against the 3000 K blackbody curve with shaded boxes indicating the cut off range for ASD calculations

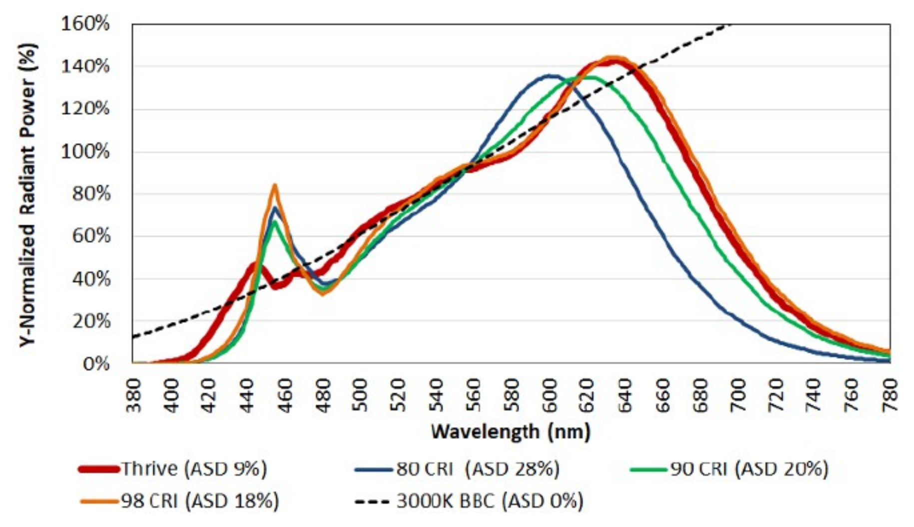


Figure 5: SPDs of 80 CRI, 90 CRI, 98 CRI, and Thrive LEDs in comparison with the blackbody curve

Evalutation Metric		3000 K BBC	3000 K Thrive	3000 K 80 CRI	3000 K 90 CRI	3000 K 98 CRI
ASD		0%	9%	28%	20%	18%
CRI	R_a	100	98	83	92	98
TM-30	R_f	100	98	84	91	94
	R_g	100	101	93	97	102

Table 1: Typical ASD, CRI, and TM-30 values for 3000K light sources

To arrive at a quantitative value for depicting the naturalness of the light source, the SPDs of each source are first Y-normalized so that they are comparable in the visible spectrum. The spectrum is then divided into 266 1 nm wide segments between the visible light wavelengths of 425 nm and 690 nm. The difference in radiometric power between the artificial light source and its reference light at each nanometer segment is measured and expressed as a percentage deviation. The absolute values of all 266 values are then averaged to produce a single value. This calculation can be expressed as an Average Spectral Difference, or ASD. Lighting professionals can compare this single value to assess the relative naturalness of different light sources under consideration.

The equation for calculating the ASD value is:

$$ASD = \frac{\sum_{\lambda=425}^{690} \left| \frac{\phi_{ref}-\phi}{\phi_{ref}} \right|_{\lambda}}{266} \tag{1}$$

The ASD value, expressed as a percentage, always compares a test source to a reference source at the same CCT. The reference source used in this calculation is the blackbody curve (BBC) for light sources of 4000 K and below, and the daylight spectrum (standard illuminants such as D50, D57, and D65) for light sources of 5000 K and above. These natural light reference spectrums are equivalent to those used by the IES for calculating TM-30 color quality metrics.

A comparison of the 3000 K LED SPDs in **Figure 5** shows the superior qualitative naturalness of the Bridgelux Thrive™ source compared to other Bridgelux standard LED sources at 80 CRI, 90 CRI, and 98 CRI. By using the newly defined ASD metric, the quantitative difference is stark. While the best of the three standard LEDs is the 98 CRI product, with an ASD of 18%, the Thrive LED has an ASD of just 9%, cutting the deviation from natural light in half.

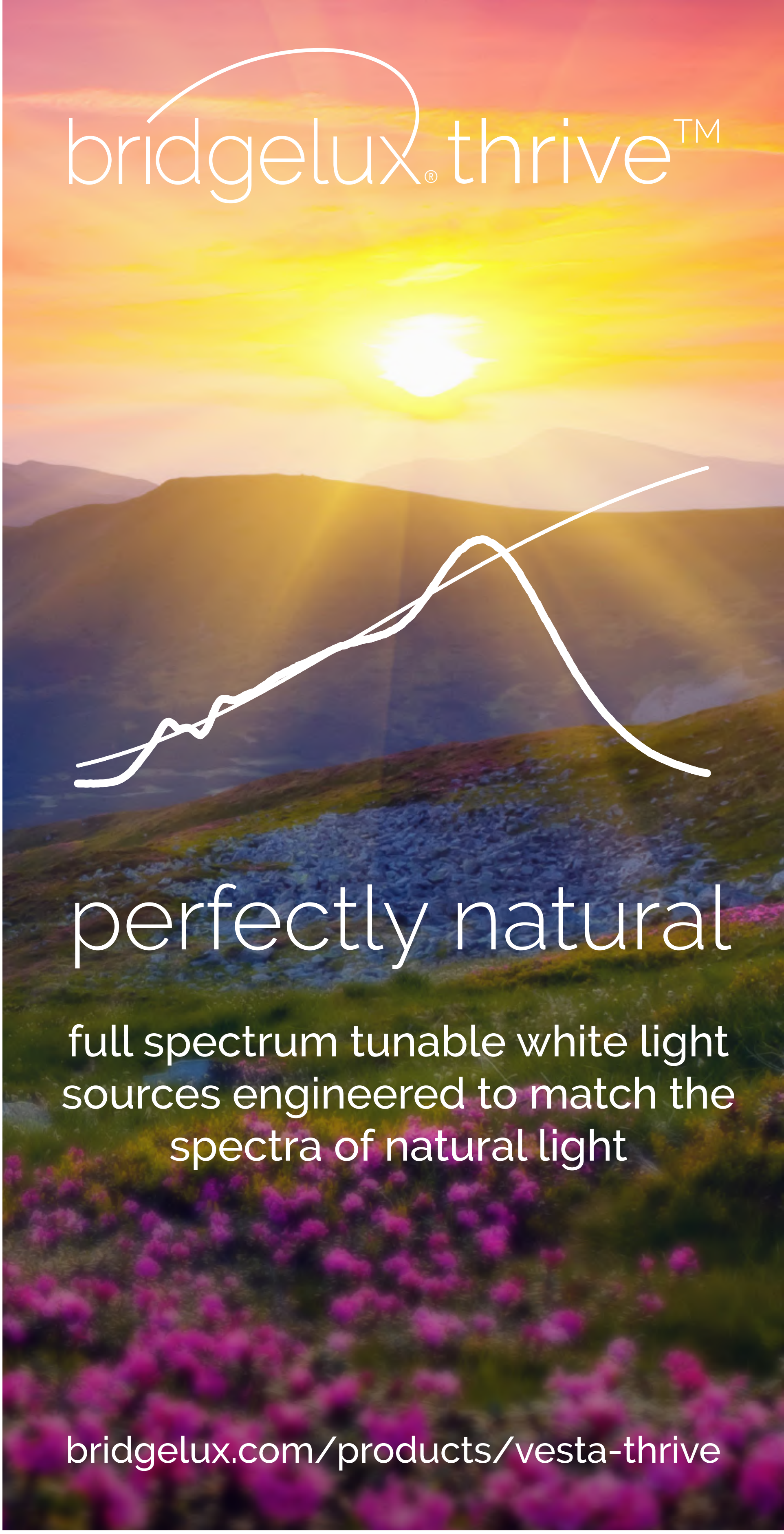
It might seem counterintuitive that the 98 CRI product would have a similar, and not significantly lower, ASD value in comparison to the 90 CRI product, however, the 98 CRI product has been spectrally engineered to deliver a high CRI, not to deliver a closer match to natural light. This validates the premise that CRI alone is not an accurate measurement of naturalness.

While high CRI and TM-30 values can be produced by a light source that has a poor (high) ASD value, a light source with a good (low) ASD value will always correspond to high CRI and TM-30 ratings due to the naturalness of the light. **Table** 1 exemplifies this by showing that the two sources with the lowest ASD values (natural light as defined by the black body curve and Thrive) have near perfect CRI, where the 98 CRI product also has a near perfect CRI but a much worse (higher) ASD.

When comparing the quality of light between two sources, it is important to understand the limits of human vision. The limit of perceptible distinction of color fidelity between two sources can be specified and is typically referred to as the just-noticeable difference. Research conducted at the California Lighting Technology Center (CLTC) at the University of California at Davis produced an interesting finding about human perception of artificial light sources using the TM-30 framework. The CLTC research suggested that if an illuminated reference color sample has $R_f \geq 92$, the average observer may not be able to distinguish between that source and the reference source, natural light. Thus, for a human observer, light sources with TM-30 R_f values ≥ 92 are essentially equivalent to reference natural light sources with R_f of 100.

Figure 6 compares the individual color sample fidelity scores of the 3000 K Thrive LED and the 3000 K 98 CRI LED. For the 3000 K Thrive LED, 97 of the 99 TM-30 color sample fidelity values are ≥ 92 with the two values below 92 still greater than 90. For the 3000 K 98 CRI LED, only 74 of the 99 color sample fidelity values are ≥ 92, with 13 of the 25 values below 92 also below 90.

While the data reported throughout this article is based on 3000 K light sources, the same comparison can of course be made for other CCTs with similar results. **Table** 2 shows the comparison of existing color quality metrics vs. ASD for Bridgelux Thrive and other Bridgelux high CRI light sources at commonly used CCTs. While there are minor differences in the CRI and TM-30 metrics, the differences in the ASD values



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between these sources are significantly higher, as this metric has been developed specifically to provide a quantitative measurement of naturalness. This data further indicates that high CRI or TM-30 values do not necessarily correlate to low ASD values, but in all cases a low ASD value corresponds to high CRI and TM-30 values.

The natural lighting spectrum delivered by the Bridgelux Thrive products can also be used to implement advanced forms of tunable human-centric lighting solutions. Tunable white lighting gives the end user flexibility and control to further personalize their environment beyond the historical limitation of only adjusting intensity through dimming. Since the CCT and SPD of sunlight changes throughout the day, having a natural spectra light source that is also SPD and CCT tunable enables spectral alignment between it and sunlight throughout the day. This approach maximizes harmony between the indoor lit environment and inhabitant circadian rhythm. Other use cases for natural tunable white sources include function-oriented lighting and personalization per individual preference.

The award winning Bridgelux Vesta Thrive products deliver full, natural spectra in an easy to use two channel tunable white solution. The Vesta Thrive spectra delivers low ASD values across the tuning range, delivering a significantly closer match to natural light than other two channel tunable white lighting options. The ASD values for a 2700–6500 K Vesta Thrive COB range from 8% to 11%.

Conclusions

The lighting industry is ready to move on from fundamental comparisons of raw lumen output and power consumption to the profound differences in the naturalness of light from one source to another. To date, quality of light metrics have been narrowly confined to color fidelity and color gamut, comparing the rendering and saturation of color with a reference light source. Users are becoming increasingly mindful of the effect of LED light on human health and well-being, driving the demand for natural lighting products which mimic the spectral power distribution of natural light sources. ASD is a comprehensive and scientifically credible metric, independent of human observation or preference variables, that marks a significant improvement on existing lighting metrics that aim to quantify the naturalness of a light source.

Existing quality metrics do not address the naturalness of light sources, and as such there has been significant interest in understanding and utilizing ASD as a new quantitative metric. Work will continue, together with industry partners, to define appropriate industry standard metrics to quantify spectral matching to natural light to enable straightforward comparisons between artificial light sources. As our industry evolves with an increased focus on human centric lighting, Bridgelux will continue to develop innovative products that transform the lit environment to mimic the naturalness of sunlight. ■

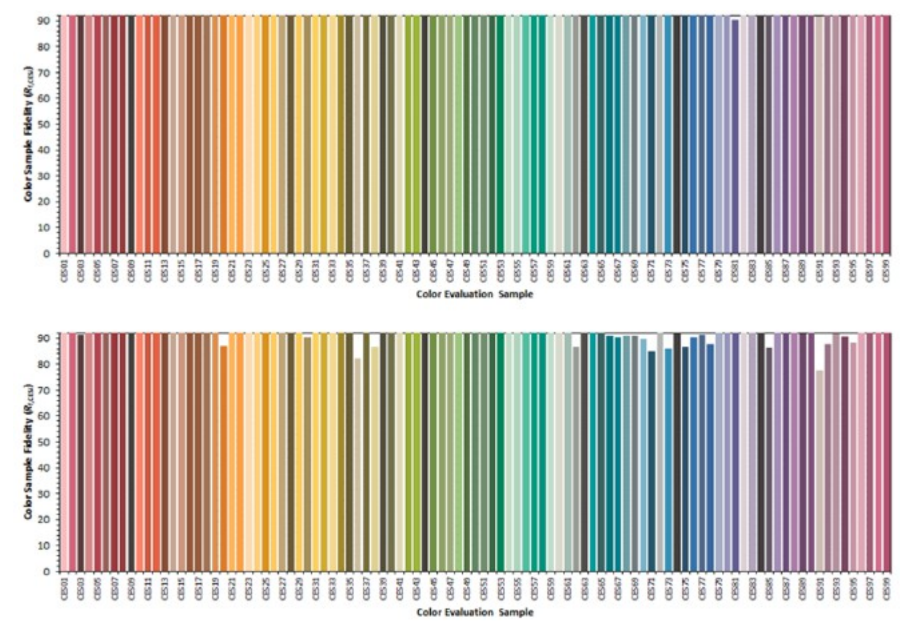

Figure 6: TM-30 Individual sample fidelity scores of a 3000 K Thrive LED (top) and a 3000 K 98 CRI LED (bottom)

CCT	Bridgelux Product	ASD	CRI R_a	TM-30 R_f	TM-30 R_g
2700 K	Thrive	10%	98	96	99
	> 95 CRI	19%	97	94	101
3000 K	Thrive	9%	98	98	101
	> 95 CRI	18%	98	94	102
4000 K	Thrive	8%	98	97	100
	> 95 CRI	18%	96	90	97
5000 K	Thrive	9%	98	97	100
	> 95 CRI	15%	96	93	100
6500 K	Thrive	8%	98	96	99
	> 95 CRI	16%	96	91	98

Table 2: Typical ASD, CRI, and TM-30 values for Bridgelux LEDs of various CCTs

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TUNABLE WHITE TECHNOLOGY INTRODUCTION OF ON-BBL TUNABLE WHITE TECHNOLOGY

Introduction of On-BBL Tunable White Technology

In a traditional tunable white solution with a combination of warm white LEDs and cool white LEDs, the chromaticity point moves linearly on the xy chromaticity diagram, while the black body locus (BBL) is curved. Due to the curvature of the BBL, especially under 3000 K CCT, the emission color withdraws from "white" with a certain range when adjusting the emission color, and it is impractical to prolong the range of correlated color temperature (CCT) toward 2000 K CCT. Tomokazu Nada, Managing Director at ZIGEN Lighting Solution, proposes a new "On-BBL Tunable White" technology that makes the chromaticity point draw an upward curve along the BBL by 2-channel control. This technology expands the possibilities of tunable white LEDs by allowing the CCT range to be set from 2000 K sunset color.

Introduction

After LED technology was adopted in lighting, a tunable white feature that can adjust emission color from warm white to cool white was provided in various lighting applications. And now, a tunable white feature is being increasingly adopted for circadian rhythm lighting.

Generally, emission colors of tunable white LEDs are achieved with a combination of a warm white LED and a cool white LED. The generated chromaticity points are located on the straight line between the chromaticity points of light source.

On the other hand, the set of white points draws an upward curve called the black body locus (BBL), on which the chromaticity points of natural light, like the sun, fire and stars are located. Thus, the farther away the chromaticity points of the two light sources are, the more difficult it is for the chromaticity points of the mixed light to follow the BBL.

For example, if a warm white LED is 2000 K CCT and a cool white LED is 5000 K CCT and both are located on the BBL, the generated chromaticity points in the middle range are more than 7 steps away from the BBL as shown in **Figure** 1. Such chromaticity points are no longer "white".

In order to keep an emission color white, a chromaticity point of a tunable white LED is required to trace the BBL on the xy chromaticity diagram as closely as possible. For this reason, a color range of a tunable white is usually set to the range where the BBL is relatively linear on the xy chromaticity diagram, such as from 2700 K CCT to 6500 K CCT or a narrower range.

However,these days, dim to warm LED technology is becoming popular in lighting and people are now aware of the importance of the 2000 K CCT Sunset Color for comfort and sophisticated lighting effects. Not only that, 2000 K color is said to be very important for circadian rhythm [1]. Thus, it is ideal to implement 2000 K CCT in tunable white lighting applications, despite the problem of the chromaticity point.

One technology to solve this problem is RGB+W LED solution.

Note that W (white color) is necessary on top of RGB (red, green, blue) for a lighting application. Because the spectrums of the RGB LED are separate from each other, the combined spectrum and color quality of the generated light become poor. This means that RGB solutions cannot be used for general lighting applications. By using the RGB+W solution, the chromaticity point can be set at the farthest point on the xy chromaticity diagram, including along the BBL by controlling each R, G, B and W LED output. However, when using the RGB + W solution, each LED output must be precisely controlled to generate a white color. Therefore monitoring intensity from each LED and adjusting output is necessary during operation. The monitoring and adjustment of each LED output is quite complicated and costs are high. Thus, most tunable white LED solutions have, so far, used a combination of warm white LEDs and cool white LEDs, but this is still a compromised solution.

In this article a new technology of tunable white, which starts from 2000 K CCT without the problem of the chromaticity point, even by 2-channel control is presented.

Basics of Color Mixing

A white LED device typically emits with a single CCT and is stable over temperature or current, because

- The wavelength of emission light from a blue LED chip is less susceptible to heat and operating current.
- Phosphor is improved to emit stable spectrum over temperature.

And stable emission color is actually one of the advantages of LED lighting. On the other hand, for achieving tunable white characteristics, it is necessary to arrange at least two sets of white LEDs with different color temperatures (typically, a combination of warm white LEDs and cool white LEDs). By adjusting the current balance between the two sets of whi

color of the mixed

The chromaticity p
in a weighted posi
from the warm wh
white LEDs. Thus,
from the warm whi
the light output fron
the chromaticity poi
closer to the chroma
white LEDs. Also, whe
from cool white LEDs i
light output from the wa
the chromaticity point of t
closer to the chromaticity p
white LEDs.

In practice, the chromaticity point
of the mixed light can be expressed b
following formula, using the chromaticity point $(x,y)_{\mathrm{warm}}$ and the luminous intensity L_{warm} of the warm white LEDs, the chromaticity point $(x,y)_{\mathrm{cold}}$ and the luminous intensity L_{cold} of the cool white LEDs.

$$(x,y)_{\mathrm{mixed}} = \frac{(x,y)_{\mathrm{warm}} \cdot L_{\mathrm{warm}} + (x,y)_{\mathrm{cold}} \cdot L_{\mathrm{cold}}}{L_{\mathrm{warm}} + L_{\mathrm{cold}}} \quad (1)$$

As can be seen from the above formula, the chromaticity point of the mixed light moves linearly between the chromaticity points of the cool white LEDs and that of the warm white LEDs.

- LED
white chann
- LED string B: connected with a cool white channel
- LED string C: connected with both warm white and cool white channels

See schematic in **Figure** 2.

The LED strings consist of LEDs connected in series, where the LEDs are LED chips or LED packages. The LED chips in the module are preferably of the same type to

Figure 1: Chromaticity points by conventional tunable white LED together with Mac Adam Ellipse (step-7) on the xy chromaticity diagram

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facturing of
LED Module.
n LED string is
position of a resin

olor of LED string A is set
olor temperature range, and
ission color of LED string B is set in
e high color temperature range. One pair of electrode terminals connected to LED string A is a warm white channel, and the other pair of electrode terminals connected to LED string B is a cool white channel.

LED strings A and B are individual LED strings that light up when a current is applied to their respective channels. LED string C is a common LED string that is electrically connected to both channels and lights up regardless of the channel. LED string C has a dedicated part and a shared part. The dedicated part is connected to respective electrode terminals and the diode characteristic of the LED prevents a current from flowing through the individual LED strings belonging to the other channel. The shared part is the LED string where a current from both channels flows through. This common LED string plays a key role in the patented "On-BBL Tunable White" technology.

With this constitution, when a current is applied to either channel, one of the individual LED strings and the common LED string light up, and a mixed light is emitted from the LED module. For example, the LED module emits a mixed light from LED string A and LED string C when a current is applied to the warm white channel. Also, the LED module emits a mixed light from LED string B and LED string C when a current is applied to the cool white channel. When a current is applied to both channels, a current flows through all LED strings, and the LED module emits a mixed light from LED strings A, B, and C.

The current balance among LED strings A, B and C changes according to the current balance between the warm white channel and the cool white channel, and the current

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