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Readying for a Color-Mixed Future Luminous efficacy on the horizon

If history repeats itself, lighting 20 years from now will be substantially different than what it is today. Twenty years ago, LEDs were a novelty, not quite ready for use in architectural lighting systems. A little more than 20 years before that, rare-earth tri-phosphor T8 fluorescent lamps were beginning to replace broadband halophosphate T12 fluorescent lamps, which themselves became the predominant source of lumens in the U.S. around the middle of the last century. At each step in this evolution, new lighting metrics have been developed to address differences in performance, and they in turn guided technology development. For example, in the 1960s it was CRI and CCT, and more recently it has been LM-79 and TM-30.

The U.S. Department of Energy's 2019 *Lighting R&D Opportunities* report projected that in about 10 years, color-mixed LED systems will have the same luminous efficacy as phosphor-converted LED products (the ubiquitous technology today). To date, the luminous efficacy of color-mixed LED systems has lagged, but some color-mixed products are on the market, and, as we have seen in the past, they are challenging the capabilities of testing protocols and performance metrics. Thus, there is an opportunity to develop new metrics and test methods to improve current practice and facilitate product development for a more energy-efficient future.

Phosphor-converted LED products use a blue LED to "pump" a broadband mix of phosphors. The combination of blue light from the pump and green-yellow light from the phosphors makes white light. In contrast, with color-mixed LED systems, the emissions of three (i.e., red, green, blue [RGB]) or more distinct emitters—usually called *primaries* or *channels*—are mixed to make white light. Either type—phosphor-converted or color-mixed—can be included in a color-tunable system, with the variability dependent on the specific LEDs that are included. For example, two phosphor-converted LEDs are often used today to produce a "white tunable" product that can vary its chromaticity but has limited variation in other performance parameters.

Architectural lighting products with up to eight LED primaries are available today, and systems designed for experimental or other specialty uses can include 18 or more primaries in the visible wavelength range. While color-mixed LEDs are expected to eventually provide the most-efficacious method for creating fixed-output products, their inherent advantage is a wide range of tunability. By varying the intensity of the individual primaries, the spectrum and all related properties can be adjusted at any time. This variability allows color-mixed LED systems to build upon their higher efficacy by adjusting their spectra to meet specific application needs.

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Today, lamps and luminaires are usually tested when operating at full power based on electrical characteristics, quantities derived from the emitted spectral power distribution (SPD), and quantities based on the luminous-intensity distribution. The engineering, design and specification of lighting products and systems are built on this information system, which is adequate in a market that is dominated by fixed-SPD light sources. With color-tunable products, however, operating at maximum potential power may never occur, and operating with the overall intensity control signal at maximum could mean one of many different output conditions. This will require new test procedures and new metrics to characterize performance in a useful way.

Some situations are relatively easy to address, such as testing at a discrete number of control inputs for tunable products that only vary the CCT—the key is having a single interval-type control for varying the spectral output. Other situations, such as products with four or more LED primaries, are a much greater challenge, because multiple combinations produce the same chromaticity of light. These combinations are called metamers, and there can be a lot of them. A five-primary LED product with 256 intensity levels for each channel can produce more than a trillion different (non-metameric) SPDs. The number of metameric SPDs depends on the specific primaries, chromaticity and tolerances but is usually in the hundreds of thousands. No matter how many, there is no single SPD or operating state that can effectively represent that lamp or luminaire's performance, with the metamers having a range of biological potential or color-rendition performance, for example.

One option for photometric testing of multi-primary, color-tunable LED systems is to measure the properties of each channel operating independently, and then combine the results mathematically to convey the range of performance. There are downsides and imprecision with this approach, because due to thermal considerations, the performance of multiple LEDs operating together will not exactly match the mathematical model based on individual LEDs. However, a reasonable approximation is likely achievable—even if the total error is not yet quantified.

AN ONGOING PROJECT at Pacific Northwest National Laboratory seeks to develop a method for calculating large metamer sets and distilling the resulting data into usable information. This work has involved creating algorithms to more efficiently calculate metamer sets, with the goal of making the calculations feasible for everyday users. The project has also involved devising new ways to summarize system performance that cover both the extent of variability and the performance levels that can be achieved—attributes that are important for product development and specification.

A set of metamers eliminates the need to perform an optimization calculation for each item of interest, or to physically test specific conditions where this performance is expected. With a set of metamers, the variation in luminous flux, color fidelity, melanopic to photopic ratio (M/P), or other spectrally derived quantities can be quantified by the range of possible values. A limitation is that the ranges for each item are not independent, which means that maximum values cannot be achieved simultaneously. An alternative is to examine a set of specification criteria that is a composite indicator of performance, examining if the criteria, or perhaps gradations of criteria, can be met. The specification criteria in ANSI/IES TM-30-18 Annex E are one example.

Performance of other spectrally derived quantities can vary with chromaticity (i.e., across different metamer sets for the same product), which can be addressed by reporting the variation in performance across CCT, or across the range of CCT over which a performance level can be met.

It is possible to aggregate information into a single number that indicates performance variability. One concept being explored is to characterize the range of possible outputs for a product operating at a specific chromaticity, by calculating the number of unique combinations for a set of individual measures. For example, the extent of color-rendition variability can be characterized by computing the unique combinations of the R_f, R_g, and hue-angle bin of the greatest Local Chroma Shift value (a proxy for gamut shape). With this approach, an SPD with $R_f = 80$, $R_g = 100$, and maximized chroma shift in hue-angle bin 1 is one combination, and a metameric SPD with $R_f = 83$, $R_g = 104$, and maximized chroma shift in hue-angle bin 7 is another. A product with greater color-rendition variability, or more possible unique output states, might be more valuable in a situation where it is used to illuminate specific objects that change over time, such as in an art gallery. Increased variability may not always be desired or offer the best solution, however, so multiple types of information are necessary.

While improved test and characterization methods will ultimately aid specification of multi-primary LED systems, they can also facilitate LED emitter development and product development. For this reason, it is important to develop methods now rather than as a reaction to the changing market. In this way, we can be working today to ensure that we'll have more-energy-efficient, higher-quality lighting 20 years from now.

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