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Application of green-emitting Sr_3WO_6:U phosphor to enhance lumen efficiency of WLEDs

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ABSTRACT

The article demonstrates a sample of spectrum in the phosphor-covered WLED (abbreviated as p-WLED) containing one blue chip, one red chip along with phosphors of green and yellow colors. We acquired the p-WLEDs' ideal spectrum in the CCTs, which is short for correlated color temperature range from 2700 K to 6500 K using a nonlinear program in order to optimize the radiation's lumen efficiency (LER) when the R9 strong red's color rendering indexes (CRIs) and special CRIs exceed 98. From the outcomes of the recreation, p-WLEDs containing an InGaN blue chip with 450 nm wavelength, an AlGaInP red chip with 634 nm wavelength, along with green and yellow silicate phosphors with the value of 507 and 580 nm wavelength correspondingly; can produce white lights with CRI values of around 98 and particular CRI values of R9 for intense reds above 98. For saturated red, yellow, green, and blue colors, the average values of the particular CRIs R9 through R12 exceed 95. In CCT values of 2700 K to 6500 K, the R13 value in female figures is around 100, with LER values reaching 296 lm/W.

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1. INTRODUCTION

According to certain predictions, the semiconductor could later dominate the traditional incandescent and fluorescent light sources in the field of general lighting thanks to the promising features such as limited power consumption, great performance, compactness, as well as great longevity [1]-[3]. The light's ability to reveal the true colors of any items is an important factor, which is measured by the CRI [4]-[6]. Lumen efficiency (lumens per electrical watt) is also an essential aspect that should be taken into account. In this article, the abbreviation LE refers to the efficiency of converting electrical energy (watt) into lumens. Two aspects control a source's LE, which include the conversion efficiency from electrical energy to light energy (radiant efficiency) and the conversion aspect from optics energy (watt) to lumen (also known as luminous). The second aspect is considered radiation's lumen efficiency (measured by lumen per optical watt), which is denoted as LER in this article. When it comes to generating white light via LEDs, two distinct methods are available. The first method involves combining the emission of many one-color LEDs to create white light [7], [8]. As the down-conversion prevents loss, such method produces white light that could have quite significant LE. In theory, the two-color white light has the greatest efficiency, LER value exceeding 440 lm/W [9]. On the other hand, such light has insignificant CRI value. In order to give CRI a substantial boost, we can raise the amount of LED with primary colors for the light [10]-[12]. But doing so can decrease the LE value. The second method utilizes phosphor components, which undergo partial down-transmission of greater photons to lower-energy photons, which happens to phosphors. Such method provides certain benefits such as compactness, one power source, along with great CRI value thanks to a phosphor's wide emission spectrum [13], [14]. The method can yield decent chromatic consistency, notably when we excite the phosphor with UV light. But the phosphor-covered WLEDs (pc-WLEDs) has low LE because of the down-conversion as well as a fairly wide emission spectrum. According to certain claims, it is possible to adjust the p-WLEDs in dual-blue emitting active region to yield greater CRI values as well as great radiation's lumen efficiency, unlike the single blue white sources [15]. But the CRI value may be quite significant to sources that are bad at showing saturated colors in objects. In recent times, the National Institute of Standards and Technology (NIST) came up with a better parameter, which is color quality scale (CQS). But the results yielded by said parameter are similar to results by CRI in the latest phosphor-based LEDs [16]. As such, the CRI can be seen as an appropriate parameter utilized in p-WLEDs that indicates the white light's efficiency in generating colors. Our research recommends the method of generating white light via p-WLED containing a blue and a red chip with green and yellow phosphors; which can solve the unremarkable transmission efficiency and LE in the red phosphor. In order to assess the optimal peak of wavelengths in said components of the p-WLED to achieve the highest LER value when the CRI value and the specialized CRI of R9 for bright red exceeds 98, the article demonstrates the sample of the spectrum in p-WLED containing blue and red colored chips. We consider the specialized CRI of R9 into account as the contrast between the red and the green shades can be essential for color generation [17], [18], and red can usually raises issues. Insufficient red element limits the duplicatable color gamut and the lighten up area could appear boring. This article also demonstrates the recreation of the p-WLEDs containing a blue InGaN chip, a red AlGaInP chip, with the silicate phosphors of yellow with green colors and red nitride phosphor in the CCT range of 2700 K to 6500 K.

2. COMPUTATIONAL SIMULATION

2.1. Preparation of green-emitting Sr_3WO_6:U phosphor

Sr_3WO_6:U is made by dissolving the U-nitrate in some methanol and then adding the solvent to the other materials. Then, to make a homogenous slurry, add methanol. The mixture undergoes two firing stages. In the first stage, heat the mixture for an hour in open quartz boats in the air at 900 ^oC, then powderize it by grinding or milling. In the second firing stage, the mixture is boiled in open quartz boats with O_2 at 1000^{o}C for two hours. The acquired phosphor emits yellow-green color, has emission peak of 2.25 eV, emission width full width at half maximum (FWHM) of 0.19 eV, excitation efficiency by UV of + (4.88 eV) and + (3.40 eV), poor excitation efficiency by e-beam, see Table 1 [19], [20].

Table 1. Compositions of the green-emitting Sr_3WO_6: U phosphor

Ingredients	Mole (%)	Weight (g)
$SrCO_3$	300	443
WO_3	100	232
$UO_2(NO_3)_2{\cdot}6H_2O$	0.2	1
Li_2CO_3	2 (of Li)	0.740

2.2. Simulation

The phosphorous layer of the actual MCW-LEDs is recreated with flattened silicone layers using LightTools 9.0 software [21]-[23]. The recreation involves two primary stages: in stage (1), we must determine and build the configuration models and light attributes of MCW-LED lamps. In stage (2), we manipulate the phosphor compounding impacts of light via many different concentrations of $CaAl_2O_4$:Mn^{2+}. To see how the phosphors YAG: Ce^{3+} and $CaAl_2O_4$:Mn^{2+} affect the output of the MCW-LED lamps, it is necessary to create certain contrasts. We need to determine the two forms of compounds at average CCT levels range from 3000 to 5000 K, conformal phosphor structure. A representation of MCW-LED lamps featuring the conformal phosphor compound and a high CCT level at 8500 K may be shown in Figure 1. It seems that $CaAl_2O_4$:Mn^{2+} is not present in the recreation of MCW-LEDs. The foot length of the reflector is 8 mm, the height is 2.07 mm, and the top surface width is 9.85 mm. The conformal phosphor compound is coated over nine chips, with each chip being 0.08-mm thick by default. With a square base region of 1.14 mm^2 and 0.15 mm in a height, all square LED chip is 1.14 mm^2 in length and a height of 0.15 mm, and is linked to the gap of the reflector. Every blue-colored chip has a radiant flux of 1.16 W with 453 nm of the peak wavelength.

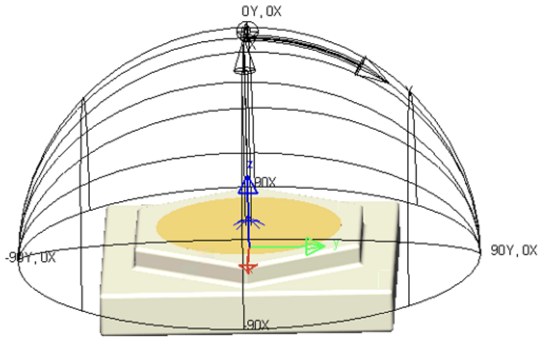

Figure 1. Photograph of WLEDs

3. RESULTS AND ANALYSIS

Figure 2 illustrates that green phosphor Sr_3WO_6:U concentration is inversely proportional to the yellow phosphor YAG:Ce^{3+} concentration, which indicates two things: first, to maintain the average CCT levels; second, to affect the absorption and scattering WLEDs' two layers of phosphor. The WLEDs' chromatic performance and lumen output can be affected in the end as a result. Therefore, the concentration of $CaAl_2O_4$:Mn^{2+} determines the WLEDs' chromatic performance. As 2% concentration raises upto 20% wt., the YAG:Ce^{3+} concentration went down to maintain the average CCT levels. Such event also applies to WLEDs in the CCT values from 5600 K to 8500 K.

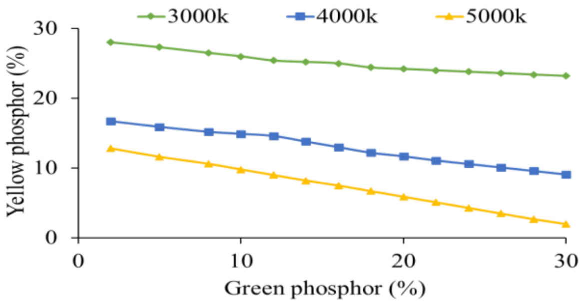

Figure 2. Changing the concentration of phosphorus to preserve the average CCT

Figure 3 to Figure 5 demonstrates how the concentration of green phosphor $CaAl_2O_4$:Mn^{2+} can influence the WLEDs' transmittance spectrum. The needs of the manufacturer can determine the option. WLEDs with significant requirement of chromatic performance may slightly decrease the lumen output. As we can see in Figure 3 to Figure 5, the combination of the spectral zone creates white light. The said figures display the spectrum at respective CCT levels of 5600, 6600, 7000, and 8500 K. It is clear that the two zones of the optical spectrum with the wavelength ranges of 420-480 nm and 500-640 nm indicate that their intensities rise accordingly to the concentration of $CaAl_2O_4$:Mn^{2+}. Such rise in the two-band emission spectrum indicates higher lumen. In addition, the scattering of blue light in WLED also displays higher activity, indicating higher activity of the scattering in the layer of phosphor and in WLED, which boosts the chromatic homogeneity as a result. Such outcome can be vital for the use of $CaAl_2O_4$:Mn^{2+}. Specifically, manipulating the chromatic homogeneity in remote phosphor package at great temperature is not an easy work. Our research verified the ability of $CaAl_2O_4$:Mn^{2+} at small and great color temperature (5600 K and 8500 K) to boost the WLEDs' chromatic performance. This article, therefore, has demonstrated the lumen efficiency in the two-layer remote phosphor layer. Specifically, in Figure 6, the lumen generated is seen to receive a substantial boost as the $CaAl_2O_4$:Mn^{2+} concentration goes from 2% wt. to 20% wt. Figure 7 shows that the color deviation displayed a considerable decrease in accordance to the concentration of phosphor $CaAl_2O_4$:Mn^{2+} at three average CCT levels. Such event could be clarified by the absorption of the red phosphor's layer. As the blue light created by the LED chip is absorbed by the blue phosphor granules, the blue light is converted to green light. Beside the blue light mentioned, the granules of $CaAl_2O_4$:Mn^{2+} also absorb the yellow light. Between the said absorptions, because of the substance's absorption features, the absorption of the blue light generated by the chip of LED displays more potency. Therefore, the WLEDs' green element is boosted when $CaAl_2O_4:Mn^{2+}$ is introduced, which boosts the chromatic homogeneity as a result. Among today's WLED lamp parameters, chromatic uniformity is considered a vital parameter. It is evident that raising the chromatic uniformity can raise the WLED's price. But $CaAl_2O_4:Mn^{2+}$ can be economical, and as such it may have widespread application.

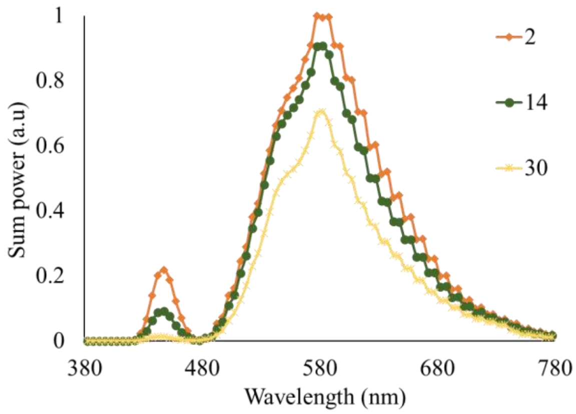

Figure 3. Sr_3WO_6:U concentration functions as the emission spectra of 3000 K WLEDs

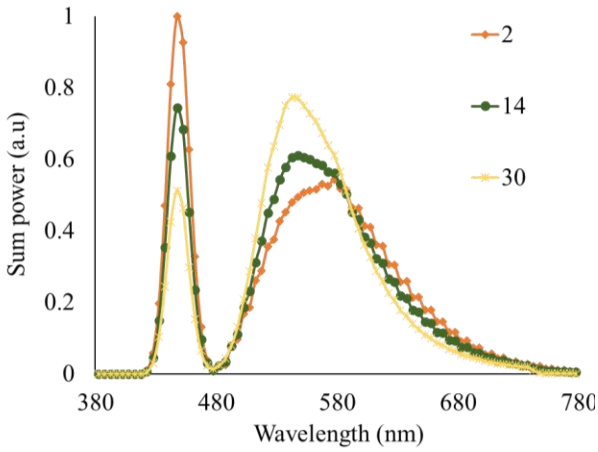

Figure 4. Sr_3WO_6:U concentration functions as the emission spectra of 4000 K WLEDs

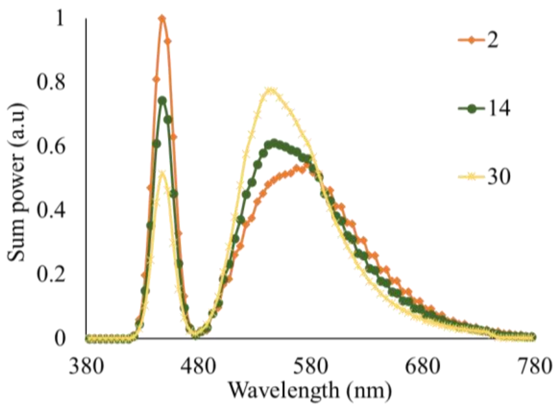

Figure 5. Sr_3WO_6:U concentration functions as the emission spectra of 5000 K WLEDs

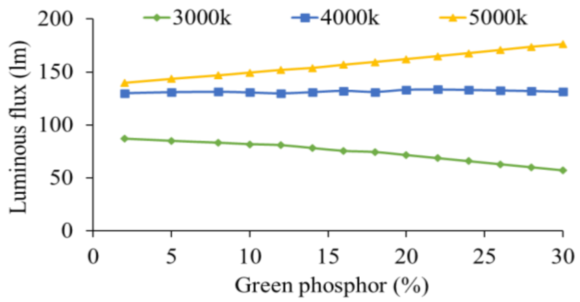

Figure 6. Sr_3WO_6:U concentration functions as the luminous flux of WLEDs

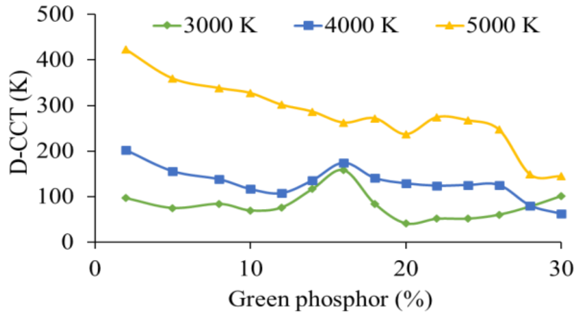

Figure 7. Sr_3WO_6:U concentration functions as the color deviation of WLEDs

When it comes to determining the WLEDs' chromatic performance, chromatic uniformity is the sole aspect. Great chromatic uniformity does not guarantee decent chromatic performance. As such, earlier studies propose a parameter to determine the color generation and chromatic quality. As a light is casted on the color rendering index, the index displays the object's genuine color. Green-light presence is overabundant among the three major colors, blue, yellow, and green, resulting in a lack of chromatic homogeneity. Such outcome has an impact on the WLED's chromatic performance, which can harm the chromatic uniformity. When the layer of remote phosphor $CaAl_2O_4:Mn^{2+}$ is added, we can see that in Figure 8, CRI decreases by a small amount. However, such drawbacks are insignificant as CRI is merely a CQS's downside. Judging both CRI and CQS, it is more difficult to acquire the CQS and the CQS should be favored over CRI [24], [25]. The CQS parameter takes into account three facets: CRI, beholder's taste, and color coordinate. With such important facets, CQS can be considered the effective, and general parameter determining the chromatic performance. With the layer of remote phosphor $CaAl_2O_4:Mn^{2+}$, the boost in CQS can be seen in Figure 9. Furthermore, as the phosphor $CaAl_2O_4:Mn^{2+}$ concentration rises, the CQS does not display any remarkable change when the said concentration is below 10% wt. If the concentration exceeds 10% wt., CRI and CQS all suffer from a considerable fall caused by the tremendous loss of color due to the prevalence of green color. As such, we must choose an appropriate concentration of green phosphor $CaAl_2O_4:Mn^{2+}$.

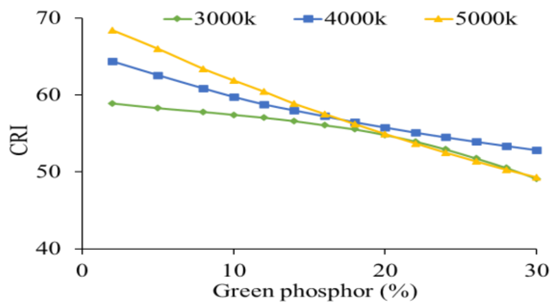

Figure 8. Sr_3WO_6:U concentration functions as the color rendering index of WLEDs

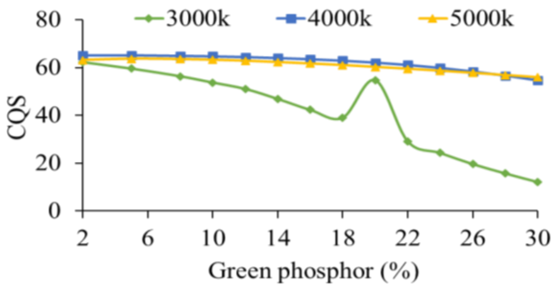

Figure 9. Sr_3WO_6:U concentration functions as the color quality scale of WLEDs

4. CONCLUSION

The optimal spectrum was obtained in p-WLEDs with a blue InGaN chip and a red AlGaInP chip, with silicate phosphors of green and yellow colors in the CCT range of 2700 K to 6500 K using a nonlinear program to optimize LER when CRI and R9 exceeds 98. For the InGaN blue chip, AlGaInP red chip, and the silicate phosphors of the color green and yellow, their ideal peak wavelengths are 450, 634, 507, and 580 nm, From the outcomes of the recreation, we can see that the p-WLEDs mentioned has the ability to generate white light having approximate CRI value of 98 and special R9's CRI exceeding 98. The average value of special R9's CRIs through R12 for the saturated red, yellow, green and blue colors is greater than 95. The value of R13 in female aspects is approximately 100, with LER value exceeding 296 lm/W in the CCT range of 2700 K to 6500 K. The LER value in p-WLED with outstanding CRI containing a blue InGaN chip, a red AlGaInP chip, with the silicate phosphors of yellow and green colors; received a boost ranging from 19% to 49%, in comparison to LER value in p-WLEDs with outstanding CRI containing an InGaN blue chip, with silicate phosphors of green and yellow colors, along with red nitride phosphor.

REFERENCES

[1] A. S. Baslamisli and T. Gevers, "Invariant descriptors for intrinsic reflectance optimization," *Journal of the Optical Society of America A*, vol. 38, no. 6, pp. 887-896, 2021, doi: 10.1364/JOSAA.414682.

[2] P. Kaur, Kriti, Rahul, S. Kaur, A. Kandasami, and D. P. Singh, "Synchrotron-based VUV excitation-induced ultrahigh quality cool white light luminescence from Sm-doped ZnO," *Optics Letters*, vol. 45, no. 12, pp. 3349-3352, 2020, doi: 10.1364/OL.395393.

[3] G. Granet and J. Bischoff, "Matched coordinates for the analysis of 1D gratings," *Journal of the Optical Society of America A*, vol. 38, no. 6, pp. 790-798, 2021, doi: 10.1364/JOSAA.422374.

[4] Y. Wang, G. Xu, S. Xiong, and G. Wu, "Large-field step-structure surface measurement using a femtosecond laser," *Optics Express*, vol. 28, no. 15, pp. 22946-22961, 2020, doi: 10.1364/OE.398400.

[5] M. Lecca, "Generalized equation for real-world image enhancement by Milano Retinex family," *Journal of the Optical Society of America A*, vol. 37, no. 5, pp. 849-858, 2020, doi: 10.1364/JOSAA.384197.

[6] M. A. Elkarim, M. M. Elsherbini, H. M. AbdelKader, and M. H. Aly, "Exploring the effect of LED nonlinearity on the performance of layered ACO-OFDM," *Applied Optics*, vol. 59, no. 24, pp. 7343-7351, 2020, doi: 10.1364/AO.397559.

[7] F. Brusola, I. Tortajada, I. Lengua, B. Jordá, and G. Peris-Fajarnés, "Parametric effects by using the strip-pair comparison method around red CIE color center," *Optics Express*, vol. 28, no. 14, pp. 19966-19977, 2020, doi: 10.1364/OE.395291.

[8] H. Q. T. Bui *et al*., "High-performance nanowire ultraviolet light-emitting diodes with potassium hydroxide and ammonium sulfide surface passivation," *Applied Optics*, vol. 59, no. 24, pp. 7352-7356, 2020, doi: 10.1364/AO.400877.

[9] Z. Zhang and W. Yang, "Tunable photoluminescence in $Ba_{1-x}SrxSi_3O_4N_2$: Eu^{2+}/Ce^{3+}, Li^+ solid solution phosphors induced by linear structural evolution," *Optical Materials Express*, vol. 9, no. 4, pp. 1922-1932, 2019, doi: 10.1364/OME.9.001922.

[10] T. W. Kang *et al*., "Enhancement of the optical properties of $CsPbBr_3$ perovskite nanocrystals using three different solvents," *Optics Letters*, vol. 45, no. 18, pp. 4972-4975, 2020, doi: 10.1364/OL.401058.

[11] M. Quesada *et al*., "All-glass, lenticular lens light guide plate by mask and etch," *Optical Materials Express*, vol. 9, no. 3, pp. 1180-1190, 2019, doi: 10.1364/OME.9.001180.

[12] J. R. Beattie and F. W. L. Esmonde-White, "Exploration of Principal Component Analysis: Deriving Principal Component Analysis Visually Using Spectra," *Applied Spectroscopy*, vol. 75, no. 4, pp. 361-375, January 2021, doi: 10.1177/0003702820987847.

[13] B. Wang, D. S. Li, L. F. Shen, E. Y. B. Pun, and H. Lin, "Eu3+ doped high-brightness fluorophosphate laser-driven glass phosphors," *Optical Materials Express*, vol. 9, no. 4, pp. 1749-1762, 2019, doi: 10.1364/OME.9.001749.

[14] Y. Wang *et al*., "Tunable white light emission of an anti-ultraviolet rare-earth polysiloxane phosphors based on near UV chips," *Optics Express*, vol. 29, no. 6, pp. 8997-9011, 2021, doi: 10.1364/OE.410154.

[15] H. Liu, Y. Shi, and T. Wang, "Design of a six-gas NDIR gas sensor using an integrated optical gas chamber," *Optics Express*, vol. 28, no. 8, pp. 11451-11462, 2020, doi: 10.1364/OE.388713.

[16] T. Ya. Orudzhev, S. G. Abdullaeva, and R. B. Dzhabbarov, "Increasing the extraction efficiency of a light-emitting diode using a pyramid-like phosphor layer," *Journal of Optical Technology*, vol. 86, no. 10, pp. 671-676, 2019, doi: 10.1364/JOT.86.000671.

[17] P. Kumar and N. K. Nishchal, "Enhanced exclusive-OR and quick response code-based image encryption through incoherent illumination," *Applied Optics*, vol. 58, no. 6, pp. 1408-1412, 2019, doi: 10.1364/AO.58.001408.

[18] J. Li, Y. Tang, Z. Li, X. Ding, L. Rao, and B. Yu, "Investigation of stability and optical performance of quantum-dot-based LEDs with methyl-terminated-PDMS-based liquid-type packaging structure," *Optics Letters*, vol. 44, no. 1, pp. 90-93, 2019, doi: 10.1364/OL.44.000090.

[19] Y. Li *et al*., "395 nm GaN-based near-ultraviolet light-emitting diodes on Si substrates with a high wall-plug efficiency of 52.0%@350 mA," *Optics Express*, vol. 27, no. 5, pp. 7447-7457, 2019, doi: 10.1364/OE.27.007447.

[20] M. J. Egan, A. M. Colón, S. M. Angel, and S. K. Sharma, "Suppressing the Multiplex Disadvantage in Photon-Noise Limited Interferometry Using Cross-Dispersed Spatial Heterodyne Spectrometry," *Applied Spectroscopy*, vol. 75, no. 2, pp. 208-215, October 2021, doi: 10.1177/0003702820946739.

[21] J. X. Yang, D. S. Li, G. Li, E. Y. B. Pun, and H. Lin, "Photon quantification in Ho^{3+}/Yb^{3+} co-doped opto-thermal sensitive fluotellurite glass phosphor," *Applied Optics*, vol. 59, no. 19, pp. 5752-5763, 2020, doi: 10.1364/AO.396393.

[22] B. Zhao, Q. Xu, and M. R. Luo, "Color difference evaluation for wide-color-gamut displays," *Journal of the Optical Society of America A*, vol. 37, no. 8, pp. 1257-1265, 2020, doi: 10.1364/JOSAA.394132.

[23] Q. Xu, B. Zhao, G. Cui, and M. R. Luo, "Testing uniform colour spaces using colour differences of a wide colour gamut," *Optics Express*, vol. 29, pp. 7778-7793, 2021, doi: 10.1364/OE.413985.

[24] Y. J. Park *et al*., "Development of high luminous efficacy red-emitting phosphor-in-glass for high-power LED lighting systems using our original low Tg and Ts glass," *Optics Letters*, vol. 44, no. 24, pp. 6057-6060, 2019, doi: 10.1364/OL.44.006057.

[25] M. Royer, "Evaluating tradeoffs between energy efficiency and color rendition," *OSA Continuum*, vol. 2, no. 8, pp. 2308-2327, 2019, doi: 10.1364/OSAC.2.002308.

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