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Full Spectrum Phosphors for White LEDs and Virtual Windows for Light and Health Applications

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Light and health is a topic of significant importance and requires fundamental studies of human interactions with light. This paper presents a review of some of the on-going studies on light and health by holistically exposing the humans to the outdoor conditions, while they are confined in indoor spaces. The designs of a new lighting-display fusion system along with examples of emerging commercial products have been presented. Full spectrum lighting is a critical component of such systems. A new simple approach for creating phosphor blends based on well known thiogallates and sulfide phosphors for designing full spectrum lighting that could replicate sunlight quality has been described. The synchronous modulation of phosphor based full spectrum light sources with electronic display playing real time outdoor videos creates a new tool for systematically studying the cognitive psycho-physiological health of human beings under different environmental conditions.

The impact of light on the human biological system, health and well-being, therapy and healing, has been a topic of wide-spread studies since ancient times. Humans evolved over thousands of years exposed to full spectrum lighting from natural and artificial sources in form of sunlight and fires. Hence the role of full spectrum blackbody radiation on the evolution of human biology cannot be undermined. Sunlight provides the full spectrum of light from ultraviolet (UV) to visible infrared (IR), all of which act on some part of human body. For example, the ultraviolet wavelength component (UVB) is responsible for creating vitamin D; the visible blue wavelength component regulates circadian functions (brain, hormones, biological cycles and clock); the green-yellow wavelength component enhances visual functions; the red wavelength component provides emotional (mood) relaxation; and the infrared wavelength component provides pain therapy. Specific wavelengths within the broad spectrum power the cells, regulate the biological clock and produce hormones, affect metabolism, provide the equivalent of vitamin C and vitamin D. Full spectrum as in sunlight have been shown to reduce eyestrain when reading and counteracts drowsiness, provide vitamin D via UV A and UVB spectrum, produce serotonin and reduces hyper-activity, stress and depression. When humans are deprived of adequate light covering the entire spectrum of wavelengths, all these biological functions start diminishing, thus negatively affecting the immune system.

In the modern day civilization, people spend most of their time indoors subjected to artificial lighting. Since the advent of electric light bulb, creating energy efficient light sources has been the priority in order to reduce energy consumption in lighting and thereby reducing environmental pollution from electric power generation using fossil fuel. In this process, significant compromises have been made toward the “quality of light” in return for higher energy efficiency. The evolution from incandescent light bulb to fluorescent lamps (FL) to lighting emitting diodes (LEDs) over the past few decades has resulted in significant alterations in the spectrum of the artificial light sources. The deviation from blackbody full spectrum in incandescent lights to discrete spectrum in FL to a spectrum enriched in blue light in LEDs have raised questions about the potential impacts of light spectrum on human health and well-being. The impact of poor lighting quality on healthcare and productivity loss related cost is enormous. A significant fraction of the healthcare cost in USA could be saved by using appropriate artificial lighting at workplace, homes, hospitals and eldercare. According to the Centers for Disease Control and Prevention, falls risk and sleep disturbances are the most common issues among older adults which are due to either poor or inappropriate lighting conditions. Amongst the shift workers including healthcare professionals, circadian disruption as a result of working at night has been linked to high blood pressure, diabetes, obesity, cardiovascular diseases and cancer. The Light Right Consortium formed by the lighting industry in partnership with the U.S. Department of Energy completed a study of the causal link between worker performance and lighting. Sleep deprivation due to lack of natural lighting exposure during the day causes drowsiness, sick leaves, higher absenteeism, higher employee turnover, increased health costs and job related accidents which cost U.S. employers 100’s of billion of dollars in lost productivity annually. Productivity loss due to sick leave, stress, eyestrain, glare, etc. has been associated with poor lighting in offices. Over the years, there have been reports of many anecdotal evidences of better lighting on the productivity related gains. Even though clear scientific evidences linking lighting quality to productivity is missing, most building owners and companies are now investigating the possibility for the right light beyond the energy efficiency goals.

The research in the field of light and health is still in its infant stages with respect to understanding the complex role of light characteristics on human well being and recovery from illness. Though the awareness for benefits of natural outdoor lighting on health has been rapidly increasing, the modern lifestyle limits the opportunity for most people to get adequate outdoor sunlight exposure. This presents a huge opportunity for future lighting designs for both commercial and residential buildings. It is necessary to shift from sheer “visibility” specifications that provide necessary illumination for occupant functions, to “lighting quality” that includes a broader range of specifications such as occupant’s health need, economic constraints, energy and environmental considerations, and architectural integration. While the spectrum and intensity of light is a huge differentiator between outdoor sunlight and indoor artificial lights, there are other factors that affects human’s interaction with light and could play a substantial role in well-being and recovery.

Recent research has started to correlate the cognitive psycho-physiological health of human beings and their interactions with nature and natural light conditions. The beneficial aspects of daylighting that impacts human spirit and the quality of life originate from the change and variety, orientation, light spectrum and view out. The important role of “windows” (view of the external environment) in indoor spaces on the productivity and well-being of occupants is becoming more evident. Psychological illnesses are common amongst patients treated in intensive care unit (ICU) without windows. Among these are seasonal affective disorder (SAD), depression, delirium, vitamin D deficiency, and circadian rhythm sleep disorders. Recovery
rate amongst hospital patients has been found to be faster for patients treated in rooms with windows having outdoor views and presences of natural lighting. However such systems fail to provide such conditions for few occupants. Providing access to outdoor views and natural lighting to every occupant in a building is a daunting task for architectural designers and often cost prohibitive when accounting for energy efficiency of the buildings.

The advent of LED based solid state lighting (SSL) enables the design of tunable full spectrum Smart lighting systems that could provide the conditions similar to natural outdoor lighting. However modulating the light spectrum and/or intensity only provides limited benefits for human biological functions. There is a need for future advancement in “holistic” lighting and display technologies that could enable the simultaneous interaction of humans with natural lighting and nature. Artificial displays using liquid crystal displays (LCD) can augment smart lighting systems and fulfill the need for view-out. Many offices and hospitals have experimented with view-out or sky-light concepts using stacked LCD panels playing pre-recorded videos of remote geographical locations as well as LED based panels creating images of passing clouds on the ceiling, etc. However such systems fail to replicate the perception and functions of a real window. Studies have shown that real time video projection using LCD unit in a room has minimal effect on human cognition beyond its entertainment value. Any artificial system replicating a real window for providing cognitive psycho-physiological therapies is desired to have the following features: (i) natural sunlight spectrum, (ii) spatial intensity profile of light inside a space based orientation of the window (north-south-east-west), (iii) continuous change in the direction of light depending on season and time of the day, (iv) dynamic variation in light intensity and spectrum due to real time weather conditions such as clouds, rain and fog, etc., (v) adequate quantity of direct light component necessary for creating shadow effects, (vi) real time outdoor view with preferably a three dimensional depth of the image, and (vii) the motion parallax effect associated with a view-out. Emerging artificial optoelectronic systems based on hybrid LED-LCD components also known as “virtual windows” are constantly evolving and are able to meet many of the above requirements. The results of clinical studies have clearly demonstrated the beneficial effect of the virtual window inside a hospital room. This paper presents (a) the design and operation of LED-LCD based virtual window systems and (b) a new approach for designing tunable spectrum phosphors and phosphor based LEDs for virtual windows and full spectrum lighting applications.

The architectural rendering of a typical virtual window system is shown in Figure 1. The unit consists of a LCD panel connected to an outdoor static video camera that plays the real time video stream of the surrounding outside the building. The static camera can be mounted to face any direction. The LCD panel is surrounded by 2 LED lighting panels on the edges. The LED panels are connected with outdoor light sensors having the same direction as the video camera. Based on the magnitude of the light levels measured by the light sensors, the electronic controller modulates the electrical power to the LED panels. Hence the illumination level provided by the LED panels replicates the real time outdoor lighting levels. The indoor lighting level provided by the LED panels is calibrated to match typical illumination levels as experienced by a real window of the same surface area. Since the light modulation and video streams are captured simultaneously by the sensors and the camera, respectively, the outputs from the LCD and LED panels are synchronized. This provides a realistic dynamic view of the outdoor conditions by the virtual window. Figures 2 and 3 show the photos of virtual windows in operation in a healthcare establishment and an office setting, respectively. These rooms originally did not have any windows. The virtual windows are able to bring the outdoor view and lighting conditions inside these spaces. One of the other features in these windows is the option to transport real time videos from remote locations with synchronized local lighting conditions as displayed in Figure 3. This is very also important for enhancing cognitive psycho-physiological treatment of patients traveling from different geographical locations.

The LED panels shown in Figures 2 and 3 are being designed using single color temperature commercial white LEDs with color temperature around 4000 K. Hence only the light intensity levels can be continuously modulated in this window system from dark to full brightness depending on the outdoor light levels. In next generations of windows, the LED panels are being designed with full spectrum phosphors (discussed below) to provide full spectrum white light based on the time of the day, season and outdoor conditions. The light sensor array in this case consists of 3 wavelength selective individual sensors measuring the blue (460 nm), yellow (560 nm) and red (630 nm) components from...
light with high CCT such as 6500 K. If a red emitting phosphor is added on the yellow phosphor, the combination of blue, yellow and red emissions produces a warm white light with low CCT such as 2800 K. By using phosphors of different emission wavelengths and different thicknesses of individual phosphor, one could fine tune the emission spectrum, CCT\(^{49,50}\) and color rendering index (CRI)\(^{51}\) of the pc-WLED. Fine tuning the CCT and CRI of pc-WLEDs by phosphor blending process is a tedious process. Uncertainties in the emission characteristics of the final product could result from slight variations in weight ratios of individual phosphors. Merely creating broad-band emission characteristics does not automatically result in high CRI values. A recent study alluded to the challenges in obtaining CRI higher than 90 except for a narrow range of CCT using phosphor blends from high quality commercially available phosphors to create full spectrum light sources.\(^{49,50}\) A new methodology was reported for fabricating full spectrum pc-WLEDs with high CRI using a single alloyed phosphor as depicted in Figure 4b.\(^{49,50}\) By simply varying the optical path length (thickness) of the alloy phosphor, the emission spectrum and thereby CCT of the pc-WLEDs could be continuously varied from cool to warm white. The phosphor alloy used in this study was selected from a general composition space of Ca\(_{1+x}\)Sr\(_{x}\)Ga\(_{1-y}\)In\(_{y}\)S\(_{2}\)Se\(_{3}\)F\(_{2}\) with (0 ≤ x ≤ 1, 0 ≤ y ≤ 2, 0 ≤ z ≤ 3) activated with Ce\(^{3+}\) and Eu\(^{2+}\). By varying the x, y and z the activator species, the emission spectrum of this multi-component phosphor could be tuned to provide either single color or broad band full spectrum LEDs. Continuing research on the role of absorption and emission by different phosphor components within this alloy matrix led to interesting phosphor blend optimization process for full spectrum LEDs. Results of creating full spectrum white light sources by changing thicknesses of optimized phosphor blends are presented below.

The outdoor sunlight spectrum recorded in Troy, New York under different weather conditions and times of day was used as the guiding metric for designing the spectrum of the full spectrum pc-WLEDs. Figure 5 shows the recorded sunlight spectra using a handheld UPRtek MK350 spectrometer. It is clearly depicted in Figure 5 that the spectra of natural lighting conditions dynamically and unpredictably change during the day. Spectrum recorded around the same time on different days could appear different with significantly different CCTs. This aspect of dynamically changing natural lighting conditions can be easily replicated in a virtual window system, while it is completely absent in artificial lighting system. In fact, artificial lighting systems have been meticulously designed to provide steady light levels. Dynamic changing lighting conditions is expected to have unintended benefits for humans such as heightened alertness levels. In general, the CCT values of sunlight varied randomly in the range of 3200 K to 5500 K during clear sunny days with CRI remaining constant around 99 (except for lower CCT around 3000 K). The highest (theoretical) value for CRI for a black body radiator and any full spectrum light source is 100. CRI less than 100 for sunlight is due to the atmospheric absorption as evident by transmission dips in the spectrum as seen in Figure 5. On a cloudy day with diffused sunlight, the CCT is significantly higher (∼9000 K), though the CRI (∼97) is not too low. Spectrum of sunlight recorded indoors after transmission through glass windows exhibited lower CRI of ∼93 with CCT ∼ 4900 K, while the CCT outside at the same time was around 5500 K with CRI of 99.

The present optimization study was focused on three specific constituent phosphors that were used in prior work to create the alloy of Ca\(_{1+x}\)Sr\(_{x}\)Ga\(_{1-y}\)In\(_{y}\)S\(_{2}\)Se\(_{3}\)F\(_{2}\) : Ce\(^{3+}\), Eu\(^{2+}\).\(^{49}\) In this work, the following three phosphors were chosen for creating broad-band full spectrum emission: (i) SrGa\(_2\)S\(_4\) : Ce\(^{3+}\), Na\(^{+}\), blue-green phosphor with peak emissions around 450 nm and 490 nm, (ii) Ca\(_3\)Ga\(_2\)S\(_6\) : Eu\(^{2+}\) yellow phosphor with peak emission around 555 nm and (iii) SrS : Eu\(^{2+}\) orange phosphor with peak emission around 625 nm. The emission efficiency of these classes of phosphor compounds strongly depends on the synthesis process with highest efficiencies reported in the range of 70–90%.\(^{51-61}\) The temperature stability (thermal quenching behavior) is not as strong as the YAG-Ce class of phosphors. Emission intensity at 400 K has been found to be around 90% of the intensity at room temperature.\(^{63}\) Phosphor in micro-crystal form grown from melt has
Figure 5. Sunlight spectrum measured in Troy, New York at different times of the day and on different days. The spectra (a-h) were measured outdoor and spectrum (i) was measured indoor (with sunlight coming through a glass window). All the spectra were recorded under bright sunny conditions except spectrum (c) which was recorded with clouds in the sky. Spectra (a-c) were recorded on 9/10/2014 at 9 am, 2 pm and 6.30 pm, respectively. Spectra (d-f) were recorded on 9/17/2014 at 9 am, 2 pm and 6.30 pm, respectively. Spectra (g-i) were recorded on 6/5/2015 at 11 am. The spectrum (g) was measured in direct sunlight, while spectrum (h) was measured in the shade. The measured CCT and CRI values are: (a) 5278 K, 99, (b) 5576, 99, (c) 8686, 97, (d) 5199, 99, (e) 5538, 99, (f) 3206, 93, (g) 5443, 99, (h) 5271, 98, (i) 4878, 93.

been found to exhibit resistance to moisture and higher luminescence stability over extended periods of time compared to solid state synthesized powders of these compounds. The phosphor blends were created by mixing various weight ratios of the three pre-synthesized phosphors in dry form and then dispersing the blend in Epoxy 20–3302 (from Epoxies, etc.) and coated on a glass slides. The weight ratio of the phosphor blend (mixed powder) to the epoxy used was approximately 1:10. The surface density of the phosphor blend was increased in the range of 0.4 to 0.8 mg/mm² for changing the CCT between 9000 K and 3500 K. The emission spectrum, CCT and CRI were measured using a hand held UPRitek MK350 spectrometer. The excitation source used was a 400 nm LED.

A systematic 4-step approach was developed and used to create a phosphor blend based on the above 3 phosphors. In the first step, increasing amount of CaGa₂S₄:Eu²⁺ powder was deposited on 1 mm² surface area of a glass slide while constantly excited by a 400 nm LED until a specific point on the (x,y) chromaticity coordinate diagram close to the Planckian blackbody locus was achieved. In the second step, the SrS:Eu²⁺ powder was added to slightly shift the (x,y) coordinate away from the Planckian locus. In the third step, the SrGa₂S₄:Ce³⁺ Na¹⁺ powder was added to bring the (x,y) coordinate back to the Planckian locus. The fourth (last) step was used to fine tune the (x,y) coordinate away from the Planckian locus. The optimum weight ratio of the yellow to red phosphors was found to be in the range of (1: 2.5-3: 18–25) for CRI above 95. Phosphor blends prepared using weight ratios in this range were used to create full spectrum LEDs within a wide range of CCTs and with CRI greater than 90. For creating LEDs with different CCTs, various amounts of the 3 component phosphor blend were used along with the 400 nm LED as the excitation source. The CCT continuously decreased with increasing amount of phosphor blend. However, the CRI was found to vary minimally across the wide CCT range. Typical spectra of these high CRI full spectrum LEDs are shown in Figure 6 within the CCT range of the sunlight that was measured outdoors.

The above approach for full spectrum lighting design is important for virtual windows. Full spectrum LED arrays prepared using the same phosphor blend with increasing path length as depicted in Figure 4b can be used for tuning the spectrum to replicate the natural light quality. By simply changing the intensity of the excitation LED array below a specific path length of phosphor layer, the spectrum can be modulated throughout the day without compromising on the intensity, color and spectrum quality necessary for visual and non-visual human functions.

While CRI has been used as a metric for many decades for benchmarking general illumination light sources, full spectrum light sources for health applications requires additional or alternative metrics for evaluating their effectiveness. Emerging color rendering metrics, such as color quality scale (CQS), circadian stimulus (CS), gamut area index (GAI), color fidelity index (CFI), color saturation index (CSI), hue distortion index (HDI), luminance distortion index (LDI), color dulling index (CDI), etc., are necessary for adequately benchmarking full spectrum light sources for various applications. The interplay between these different color rendering indexes requires further research. In general, it is expected that a full spectrum light source could be tailored to simultaneously provide higher values for most of these indexes.
In summary, this paper presents a brief review of the potential impacts of natural light on human health and well-being. A compelling case for the technological development of virtual windows in conjunction with full spectrum LED-based light sources has been made based on human interaction with nature and natural lighting. Examples of new artificial window designs used in healthcare and office environments have been discussed. A new approach for the development of unique phosphor blends for tunable full spectrum light sources has been described. Using a single phosphor blend, full spectrum LEDs with high CRI and a wide CCT range replicating sunlight quality has been demonstrated. Future medical and work place productivity studies based on virtual windows providing the outdoor view along with full spectrum LEDs enabling sunlight quality lighting are now possible under calibrated conditions in indoor spaces, which will help quantify the impacts of natural conditions on human health and well-being.

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