Multi-Spectral LED And Laser-Based Solid-State Lighting And Visible Light Communication

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Abstract

Green photonics focuses on reducing global carbon footprints by developing energy-efficient solid-state lighting (SSL). Currently, it relies on LEDs in which yellow phosphor (often cerium-doped Yttrium Aluminum Garnet, YAG:Ce) is excited by blue light source to generate white light. The widespread adoption of LED technology is facing three challenges: first, low brightness due to efficiency droop. Secondly, poor color rendering due to spectral deficiency, which affects visual comfort and circadian rhythm; and third, the blue light hazard to the retina. Beyond general illumination, LEDs simultaneously facilitate optical wireless communication, typically known as visible light communication (VLC), for next-generation energy-efficient architecture. VLC provides secure and electromagnetic interference-free data transmission by modulating light from luminaires, thus integrating illumination and communication simultaneously. Research studies lack the impact of varying spectral compositions, such as color-biased hue versus a balanced, sun-like spectrum, on both the human visual system and simultaneous data communication. Laser-based solid-state lighting (LBSSL) offers high brightness due to low efficiency droop, high color quality due to spectral purity, and low blue hazard resulting from a narrow spectral width. Methods and effects of light generation, heat mitigation, and simultaneous data communication on both the human eye and the communication link are presented in the thesis.

The thesis begins with the experimental design of a lamp featuring six multi-color phosphor-converted LEDs. The illumination properties and communication properties are compared using an intensity modulation direct detection link. In contrast to a conventional white LED (CRI 77), the designed multi-color lamp exhibits a 16% higher color rendering index (CRI 90) and a 31% improvement in detection speed. This is due to a faster rise time and a 39% reduction in jitter at 1 kbps over an angular span of 120 degrees. Limitations such as brightness data rates, color fidelity, bandwidth, and transmission distance are addressed by a high-power laser-based communication link exciting four types of multi-color phosphors. Results shows a high CRI of 96 at a data rate up to 20 kbps with a 91% reduction in blue light hazard compared to conventional white LEDs. High-power LBSSL sources are not commercial due to need of expensive cooling substrates such as diamond or sapphire. Also, the cooling substrates are opaque and thus offer reflective mode of illumination, requiring additional optical components for white light-based applications. To simplify this, an indium tin oxide (ITO) coated glass, is proposed as a novel substrate for transmissive LBSSL. The conductive thin film of ITO serves as a heat exchanger between the phosphor and the glass substrate due to its high conductivity in the transverse plane due to 1.5 times higher effusivity than that of glass. Non Destructive and destructive testing at low (1 W/cm^2) and high laser intensity (127 W/cm^2) shows five-fold and three-fold reduction in degradation rate, respectively, validated by thermal imaging with a 9.0% reduction in active heating area as compared to glass while preserving colorimetric properties. In conjunction with YAG:Ce, a multi-phosphor arrangement architecture, including pixelated and stacked configurations, is modeled using an electro-thermal circuit based on thermal resistance and capacitance, photoluminescence decay lifetime, Debye temperature, and thermal capacitance to identify the optimal combination for illumination. The model reduces the number of trials required for phosphor configuration testing and searching strategy for thermally stable and optically broad spectra. So far, the developed light sources are continuous in the visible spectrum, but bio-medical applications require multispectral white light with discrete narrowband laser lines. Therefore, 7×1 multimode fiber couples the six lasers to yield white light (high CRI-93). A microcontroller precisely controls the digital intensity modulation of each laser, at the same biasing current. A liquid lightguide (LLG) reduces inherent mixed speckles (11% generated by the superposition of lasers) to 2%. The colored image transmission under saline (35 parts per thousand) and turbulent (Reynolds number 16400) underwater medium communication link is sent using quadrature amplitude modulation and received with finite impulse response based adaptive equalization technique. This thesis presents a holistic view of the white light generation, heat mitigation, and data communication.