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Quantum-Dot-Based Solid-State Lighting With Electric-Field-Tunable Chromaticity

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Abstract—**Solid-state lighting is currently based on blue light-emitting diodes combined with wavelength downconversion via phosphors. Replacing the phosphors with quantum dots has a number of potential advantages, including narrowband and size-tailorable emission spectra. Here, we point out another advantage: the ability to perform real-time tuning of chromaticity of solid-state lighting by altering quantum dot absorption or emission wavelengths and oscillator strengths using electric fields. We discuss a possible architecture for such a solid-state lamp, and the chromaticity ranges that could be obtained for given ranges of absorption or emission wavelength and oscillator strength changes.**

Index Terms—**Chromaticity control, color temperature, light-emitting diode, liquid crystals, quantum dots, quantum yield, smart lighting, solid-state lighting, Stark effect, wavelength downconversion.**

I. INTRODUCTION

SINCE their invention in 1999 [1], phosphor-converted light-emitting diodes (PC-LEDs), in which blue or purple/UV LEDs are combined with one or more wavelength-downconversion phosphors, have become the standard architecture [2], [3] for solid-state lighting. For a future generation of "smart" solid-state lighting [4], however, features which are difficult for PC-LED architectures, such as real-time tunable chromaticity, would be desirable. Tunable chromaticity would enable light to be tailored to the environment in which it is being used even as that environment changes over the course of the day. Human preference, e.g., for white light with different color temperatures depending on use and time of day in a variety of settings (residential, commercial, industrial, outdoor, automotive) could be accommodated, with anticipated improvements in human productivity, comfort and health [5].

Realization of real-time tunable chromaticity with current technology, however, introduces optical and electrical complexity as well as cost. The complexity and cost stems from the need to optically color mix laterally placed, independently electrically driven monochromatic red, green and blue (RGB) or red, yellow, green and blue (RYGB) light sources. This is true whether the individual light sources are monochromatic LEDs [6], [7] lasers [8], or, in the absence of efficient green, yellow and/or (shallow) red LEDs (for the so-called "green gap"; see, e.g, [9]), monochromatic PC-LEDs [10]–[12], or a combination of PC-LEDs plus red LEDs [13].

Recently, quantum dots (QDs) have emerged [14]–[18] as possible replacements for phosphors in solid-state lighting based on wavelength downconversion. QDs bring many advantages (some types of QDs can also have disadvantages, of course, such as thermal and photo instability, over phosphors, which represent challenges to widespread adoption, see, e.g., [19], [20]), over phosphors, including: narrow-linewidth emission for spectra which better optimize the envelope of achievable luminous efficacies and color rendering quality [21]–[23]; broadband absorption which enables selection of the blue LED wavelength to optimize white light spectra rather than absorption by the phosphor; and emission wavelengths easily tailorable through quantum size effects [24]–[26].

In this paper, we point out another advantage of QDs: the potential ability to alter, using electric fields, their absorption or emission wavelengths and oscillator strengths. Altered absorption or emission wavelengths and oscillator strengths imply an altered chromaticity of the resulting white light. If two or more QD layers were stacked on top of the blue LED, and were independently electrically biasable, then real-time tunable chromaticity could be realized *within* the current standard PC-LED architecture for solid-state lighting, without the need for optical color mixing of laterally placed sources.

To explore the feasibility of such an approach, we analyze in this paper the idealized QD-based solid-state lamp with potentially electric-field-tunable chromaticity illustrated in Fig. 1. The system consists of a blue LED topped by red and green wavelength-downconversion layers comprised of QDs dispersed in some matrix. Some of the blue LED light leaks through the QDs while some is absorbed and re-emitted as red and green light. The combination of blue, green and red light gives a white light whose characteristics (color temperature, luminous efficacy of radiation, color rendering quality) depend on the wavelengths (λ_B, λ_G, and λ_R) and spectral widths ($\Delta\lambda_B$, $\Delta\lambda_G$, and $\Delta\lambda_R$) of the blue, green and red light, as well as on the red-to-blue (p_R/p_B) and green-to-blue (p_G/p_B) power ratios.
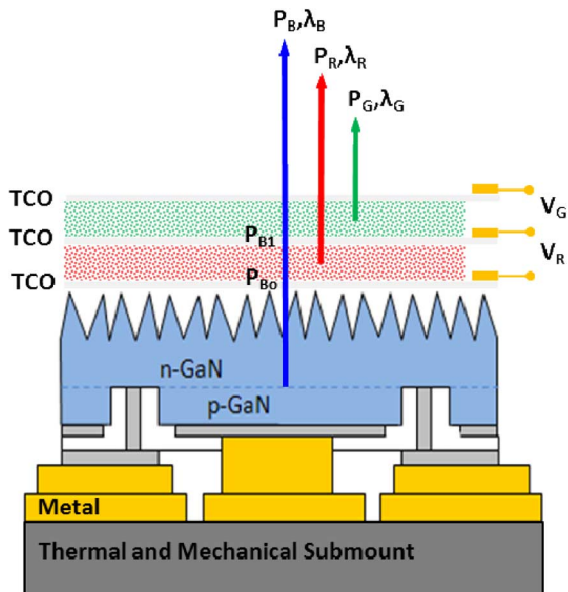
Fig. 1. An idealized LED lamp with the potential for electric-field-tunable chromaticity. The lamp consists of a blue LED that has been top-surface roughened, bottom-surface metallized, and flip-chip mounted on a thermal and mechanical submount (diagram courtesy of Jon Wierer). The LED is coated with red and green wavelength-downconversion materials embedded in dielectric (insulating) matrices and sandwiched by transparent conducting oxide (TCO) contacts. The transparent conducting oxide contacts enable voltages V_G and V_R (and associated electric fields) to be applied to the wavelength-downconversion materials.

For this idealized lamp, we calculate the chromaticities that could be obtained, in Section II, for given ranges of change in emission wavelengths, and, in Section III, for given ranges of change in absorption or emission oscillator strengths. Note that, in practice, changes in emission wavelength, and in absorption or emission oscillator strengths, might occur simultaneously. However, to understand the separate effects of such changes, we calculate in this article only the effects of each change independently of the other changes.

We also discuss some of the advantages and disadvantages to utilizing these various kinds of changes, including: how color rendering quality and luminous efficacy change as chromaticity is tuned; and the practical possibilities for achieving desirable ranges of chromaticity tuning. We discuss these practical possibilities only superficially, however, as these possibilities will depend strongly on the details of the QDs themselves and their environments.

II. CHROMATICITY TUNING VIA WAVELENGTH TUNING

We begin with the use of wavelength shifts to tune chromaticity. For concreteness, we assume white light with an initial neutral-white color temperature of 4400 K. We choose initial wavelengths ($\lambda_B = 460$ nm, $\lambda_G = 536$ nm, $\lambda_R = 613$ nm) which maximize luminous efficacy of radiation (LER) for reasonably high color rendering quality, and which are readily available from commercial blue LEDs and commercial green and red QDs. We also choose spectral (FWHM) widths ($\Delta\lambda_B = 20$ nm, $\Delta\lambda_G = 40$ nm, $\Delta\lambda_R = 30$ nm) which are readily achievable in blue LEDs and in green and red QDs,

with a slightly wider spectral width for the green than the red QDs to improve color rendering quality.

With these choices, we calculate that: the red-to-blue and green-to-blue power ratios are $p_R/p_B = 1.70$ and $p_G/p_B = 1.69$ (for these and all other white light calculations, we used a white-light simulator based on [27]); the white light luminous efficacy of radiation (LER) is 352 lm/W; the white light maximum luminous efficacy of source (MaxLES), assuming a 100% efficient blue LED and power-downconversion efficiencies limited only by the Stokes shifts, is 295 lm/W; and the white light standard color rendering index (CRI) and color quality scale (CQS [28]) are both a relatively high 88.

In the usual configuration, the color temperature and wavelengths of the white light would be fixed during fabrication by the amounts and geometry of the wavelength-downconversion materials. Here, however, we seek to tune the color temperature by tuning the wavelengths of the downconverted green and red light in the extreme case in which the red-to-blue (p_R/p_B) and green-to-blue (p_G/p_B) power ratios are held fixed. As mentioned above, this is an idealized extreme case which is of interest to analyze whether or not it is actually realizable. However, we note that it is potentially realizable if radiative recombination in the QDs were much faster than non-radiative recombination, so that quantum yields are near unity and relatively independent of changes in emission oscillator strengths which might accompany shifts in emission wavelength with applied electric field.

The necessary wavelength shifts, and the resulting changes in luminous efficacies and color rendering quality, are shown in Fig. 2. As illustrated in Fig. 2(a), as color temperature increases from 4400 K, the wavelengths of the green light must shift to shorter wavelengths and the red light must shift to longer wavelengths. Conversely, as color temperature decreases from 4400 K, the wavelengths of the green light must shift to longer wavelengths and of the red light to shorter wavelengths.

The reasons are the following. On the one hand, higher-color-temperature white light must contain relatively more lumens in the blue and relatively fewer lumens in the green and red. Since the red-to-blue and green-to-blue power ratios are held fixed, the only way to decrease the relative red and green lumen content is to decrease the red and green luminous efficacies of radiation, which means shifting their wavelengths "outwards" away from the 555-nm wavelength at which LER maximizes. On the other hand, lower color-temperature white light must contain relatively fewer lumens in the blue and relatively more in the green and red. Since the red-to-blue and green-to-blue power ratios are held fixed, the only way to increase the relative red and green lumen content is to increase the red and green luminous efficacies of radiation, which means shifting their wavelengths "inwards" toward the 555-nm wavelength at which LER maximizes.

One consequence of these wavelength shifts outward from or inward toward 555 nm is illustrated in Fig. 2(b). As color temperature increases or decreases from 4400 K and as the component red and green LERs decrease or increase (respectively), the overall white light LER and maximum achievable luminous efficacy of source (MaxLES) also decrease or increase (respectively).
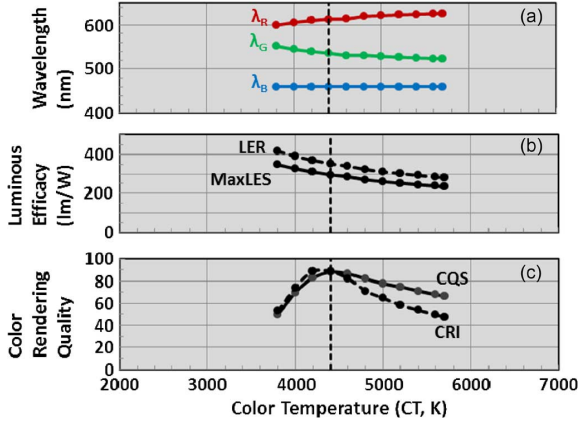
Fig. 2. (a) Wavelengths necessary to achieve various color temperatures around that (4400 K) at which the initial wavelengths were chosen for maximum LER at CRI = 85. The blue LED wavelength is fixed, as are the red-to-blue (p_R/p_B) and green-to-blue (p_G/p_B) power ratios. Note that, as Stark shifts are always red shifts, to achieve the sign of the wavelength shifts illustrated here, the green QD layer would need its zero-electric-field wavelength fixed at the high end of the desired color temperature range, while the red QD layer would need its zero-electric-field wavelength fixed at the low end of the desired color temperature range. (b) Accompanying changes in luminous efficacies of radiation (LER) of the composite white light, and maximum luminous efficacies of source (MaxLES) assuming a 100% efficient blue LED and power-downconversion efficiencies limited only by the Stokes shifts. (c) Accompanying changes in color rendering quality, as measured by the color quality scale (CQS) and the standard color rendering index (CRI), as color temperature is changed.

Another consequence of these wavelength shifts is illustrated in Fig. 2(c). As color temperature increases or decreases from 4400 K, the wavelengths shift away from those for which luminous efficacy of radiation was maximized for reasonably high color rendering quality, color rendering quality decreases. On the low color temperature side, the decreases in CRI and CQS are similar, but on the high color temperature side, the decrease in CQS is slightly less pronounced. The reason is that the impact of a shift of the red light to deeper red on color rendering quality somewhat compensates for the impact of a shift of the green light to shallow green, and the compensation is better for the CQS than for the CRI due to the CQS' greater weighting of deep red color components.

Regardless of which measure is used, color rendering quality drops off as one tunes color temperature away from that for which the red and green color components were optimized, and it is this drop-off that limits the color-temperature tuning range. The color-temperature range over which color rendering quality is sufficient can of course be shifted by choice of the color temperature at which the initial wavelengths were optimized at, but the range will necessarily be limited. For our choice of color temperature (4400 K) at which the initial wavelengths were optimized: if we would like a CQS that is 70 or higher, then the color-temperature tuning range is limited to 4050–5450 K, a range of 1400 K; but if we would like a CQS that is 80 or higher, the color-temperature tuning range is limited to 4150–4900 K, a range of only 750 K. These tuning ranges of course will depend on initial choice of color temperature, and it would be interesting to study these ranges more comprehensively, particularly for lower initial choices of color temperatures that would be of interest to residential lighting.

Finally, to understand whether there are physical mechanisms that would enable reasonable color-temperature tuning ranges, consider the magnitudes of the necessary wavelength shifts. If we would like a color-temperature tuning range of 4050–5450 K (thus maintaining a CQS that is 70 or higher), then the green and red wavelength tuning ranges would need to be 19 nm $= 544 - 525$ nm and 18 nm $= 606 - 624$ nm. If we would like a color-temperature tuning range of 4150–4900 K (thus maintaining a CQS that is 80 or higher), then the green and red wavelength tuning ranges would need to be 11 nm $= 541 - 530$ nm and 11 nm $= 609 - 620$ nm.

The necessary wavelength shifts are thus relatively large, and it is not obvious whether they are practically achievable. The application of a static electric field to semiconductor heterostructures results in level shifting of the confined electrons and holes (Stark shifts) which in turn lead to shifts in the emission spectra when radiative recombination occurs [32]–[34]. These spectral shifts can be large for some geometries and/or dimensionalities. However, in the case of spherical QDs, typical Stark shifts in the emission wavelength, for reasonable electric fields, are on the order of several-nm [29] and thus are not likely by themselves to shift the chromaticity coordinates of the resulting white light significantly.

Note, though, that somewhat larger Stark shifts can be obtained with non-spherical particles (quantum rods). In addition, for both spherical and non-spherical geometries, the Stark shifts may be accompanied by decreases in oscillator strength and perhaps quantum yield [30], [31] (as discussed in Section III), and might be used in conjunction with these decreases to tune chromaticity coordinates.

III. CHROMATICITY TUNING VIA POWER-RATIO TUNING

Now we turn to the use of power-ratio shifts to tune chromaticity. For concreteness, we again choose wavelengths ($\lambda_B = 460$ nm, $\lambda_G = 536$ nm, $\lambda_R = 614$ nm) which maximize luminous efficacy of radiation for reasonably high color rendering quality (for these and all other white light calculations, we used a white-light simulator based on [27]), and which are readily available from commercial blue LEDs and from commercial green and red QDs. The wavelengths are slightly different from those of Section II because, as discussed later, we have optimized here for a slightly warmer (2700 K rather than 4400 K) color temperature. Just as in Section II, though, we choose spectral (FWHM) widths ($\Delta\lambda_B = 20$ nm, $\Delta\lambda_G = 40$ nm, $\Delta\lambda_R = 30$ nm) which are readily achievable in blue LEDs and in green and red QDs, with a slightly wider spectral width for the green than the red QDs to improve color rendering quality.

Unlike in Section II, when we varied the red and green wavelengths but kept the red-to-blue (p_R/p_B) and green-to-blue (p_G/p_B) power ratios fixed, in this Section we keep the red and green wavelengths fixed and allow the red-to-blue (p_R/p_B) and green-to-blue (p_G/p_B) power ratios to vary so as to vary the color temperature of the composite white light.

Fig. 3(a) shows the spectral power distributions associated with two extreme color temperatures: 2700 K and 6500 K. Note that these two extremes span the range of color temperatures
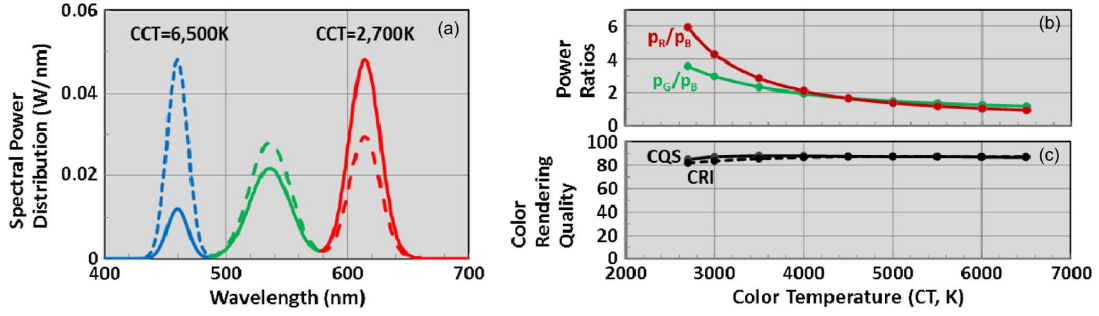
Fig. 3. (a) Hypothetical spectral power distributions from a lamp emitting 1 klm at the wavelengths and spectral widths discussed in the text, for two extreme color temperatures: 2700 K (solid line) and 6500 K (dashed line). (b) Red-to-blue and green-to-blue power ratios necessary to tune color temperature from 2700 K to 6500 K. (c) Color rendering quality, as measured by the color quality scale (CQS) and the standard color rendering index (CRI), is relatively high and constant for all color temperatures, given our choice of wavelengths and spectral widths.

used in nearly all of today's general-illumination applications, and that a more modest range of 3000 K–5000 K would likely be sufficient for many applications.

Fig. 3(b) shows more systematically the red-to-blue (p_R/p_B) and green-to-blue (p_G/p_B) power ratios necessary to produce a wide range of color temperatures. As color temperature increases, power shifts from the red and green to the blue, with the necessary red-to-blue power ratio decreasing faster than the green-to-blue power ratio due to a simultaneous power shift from the red to the green. Note that, to achieve the full 2700 K to 6500 K color temperature tuning range, the power ratio shifts are relatively large: from 5.9 to 0.9, or a factor of 6.4, for the red-to-blue power ratio; and from 3.6 to 1.2, or a factor of 3.1, for the green-to-blue power ratio.

Finally, Fig. 3(c) shows how color rendering quality changes as color temperature is tuned via power ratio tuning. Because of the choice of wavelengths and spectral widths, color-rendering quality is high throughout the entire range of color temperatures. The standard color rendering index (CRI) is in the range 82–88, the R_9 index is in the range 40–90, and the color quality scale (CQS) is in the range 85–88. Note that this maintenance of color rendering quality over a wide color-temperature tuning range is a major benefit to the power-ratio tuning considered in this Section III over the wavelength tuning discussed previously in Section II.

The power-ratio ranges illustrated in Fig. 3(b) are those that one would like to achieve. There are two ways to alter such power ratios: the first way is to alter the QD absorption oscillator strengths; the second way is to alter the QD power-downconversion efficiency (essentially the QD quantum yield but with a Stokes deficit taken into account).

To calculate the changes in QD absorption oscillator strength and/or power-downconversion efficiencies necessary to achieve these power-ratio shifts, we write the red, green and blue powers as

$$p_R = \alpha_R S_R p_{Bo}$$
$$p_G = \alpha_G S_G (1 - \alpha_R) p_{Bo}$$
$$p_B = (1 - \alpha_R)(1 - \alpha_G) p_{Bo} \qquad (1)$$

where p_{Bo} is the amount of blue light initially emitted by the LED, α_R and α_G are the potentially field-tunable fractions of that blue light absorbed by the red and green wavelength

downconverters, and S_R and S_G are the potentially field-tunable power-downconversion efficiencies of the red and green wavelength downconverters.

The absorptions α_R and α_G are proportional to the absorption oscillator strength of the QDs; and the power-downconversion efficiencies S_R and S_G are related to the emission quantum yields of the QDs. In this simple treatment, we do not include absorption of back-scattered green light by the red wavelength downconverter.

The power ratios of red-to-blue and green-to-blue light are thus

$$\frac{p_R}{p_B} = \frac{\alpha_R S_R}{(1 - \alpha_R)(1 - \alpha_G)}$$
$$\frac{p_G}{p_B} = \frac{\alpha_G S_G}{(1 - \alpha_G)} \qquad (2)$$

and the absorptions and/or power-downconversion efficiencies necessary to obtain these power ratios are:

$$\alpha_R = \frac{S_G \left(\frac{p_R}{p_B} \right)}{S_R \left[S_G + \left(\frac{p_G}{p_B} \right) \right] + S_G \left(\frac{p_R}{p_B} \right) \right]}$$
$$\alpha_G = \frac{\left(\frac{p_G}{p_B} \right)}{S_G + \left(\frac{p_G}{p_B} \right)} \qquad (3)$$

and

$$S_G = \left(\frac{p_G}{p_B} \right) \frac{1 - \alpha_G}{\alpha_G}$$
$$S_R = \left(\frac{p_R}{p_B} \right) \frac{(1 - \alpha_R)(1 - \alpha_G)}{\alpha_R}. \qquad (4)$$

Applied electric fields might affect absorption, power-downconversion efficiency, or both. Here, we examine the two cases separately: absorption changes while keeping power-downconversion efficiency fixed, and power-downconversion efficiency changes while keeping absorptions fixed.

A. Power-Ratio Tuning via QD Absorption Tuning

Let us first consider the case in which absorption is altered, but power-downconversion efficiency is not. Then, assuming quantum yields are high and near-unity, we set
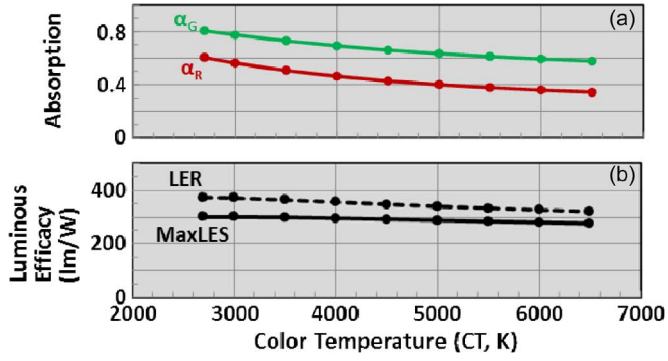
Fig. 4. (a) Absorptions (at constant power down efficiencies) necessary to achieve the power ratios in Fig. 3(b). (b) Luminous efficacies of radiation (LER) associated with the emitted power spectral distribution, and maximum luminous efficacies of source (MaxLES) assuming a 100%-efficient blue LED and power-downconversion efficiencies limited only by the Stokes shifts.

$S_R = 460/614 = 0.75$ and $S_G = 460/536 = 0.86$, the maximum power-downconversion efficiencies taking into account only the blue-to-red and blue-to-green Stokes shifts. Then, from (3) and as illustrated in Fig. 4(a), the necessary absorptions of the red and green QDs only need change from 0.60 to 0.34 and from 0.81 to 0.58, respectively, to tune the color temperature of the resulting white light from 2700 K to 6500 K. The reason is that there actually isn't much blue light leaking through the QDs; most is converted. Thus, small absorption changes lead to significant changes both in the residual amount of blue light leaking through and in the amount of downconverted red and green light, thereby giving disproportionate changes in the red/blue and green/blue power ratios.

Also in this first case, power-downconversion efficiency can be fixed at a high value, with only absorption changing, so luminous efficacy changes only according to the human eye response. As illustrated in Fig. 4(b), the maximum luminous efficacy of source (MaxLES) achievable (assuming a 100%-efficient blue LED and power-downconversion efficiencies limited only by the Stokes shifts) does decrease gradually with color temperature, but only slightly. Most of the decrease in MaxLES is due to the well-known decrease in luminous efficacy of radiation (LER) with increasing color temperature (due to spectral power shifting from the red, where the human eye is relatively more sensitive, to the blue, where the human eye is relatively less sensitive) [21]–[23]. As illustrated in Fig. 4(b), the decrease in MaxLES is actually less than the decrease in LER, because it is offset somewhat by the decreased influence of the Stokes shift as spectral power shifts from the red to the blue.

Note that this first case is nearly ideal: as color temperature is tuned, color rendering quality and luminous efficacies are maintained. However, from a physical mechanism point of view, it is not clear whether the necessary absorption changes are possible, particularly the absorption of blue light by QDs tuned to emit in the green or red.

As discussed in Section II, it is well known [32]–[34] that electric fields cause a spatial separation of the electron and hole, and hence a decrease in the cross-section for light absorption. These changes in absorption cross-section are most pronounced near the band edge, and if the band edge has been tuned to the green or red, absorption in the blue is likely to be into high-lying levels far from the band edge where changes in absorption cross-section are typically small [34]–[36].

However, there are at least two ways by which the blue absorption could be changed by an electric field. The first is through energy transfer from an absorbing quantum dot to proximal emitting quantum dots. If the absorption onset of the former is close to the blue emission wavelength, then small changes in the absorption onset wavelength could result in significant changes in the amount of light absorbed. A second, and perhaps more practical, way to tune the blue absorption is through orientational effects in non-spherical QDs. An electric field can orient a non-spherical QD, and local field effects can significantly change (by about 10%) the absorption cross section of rod-like quantum dots [37]. Alternatively, very large absorption ratios (>10) can be obtained at low electric fields if non-spherical QDs with anisotropic absorption cross-sections are guests in a liquid-crystal environment [38]. Low electric fields can orient the liquid crystal and, in so doing, also orient the QDs. A significant disadvantage of this type of scheme, though, is that the QDs must be in a liquid to facilitate reorientation.

B. Power-Ratio Tuning via Power-Downconversion-Efficiency (or Quantum Yield) Tuning

Let us second consider the case in which tuning is achieved not by altering absorption, but power-downconversion efficiency. (This has been reported experimentally for colloidal QDs. See, for example, [39]). Assuming quantum yields are high and near-unity in the *absence* of an electric field, and assuming the absorptions have been set to give the correct power ratios at the lowest (2700 K) color temperature, we can rewrite (4) as

$$S_G = (0.86) \frac{\left(\frac{p_G}{p_B}\right)}{\left(\frac{p_G}{p_B}\right)_{CT=2700 \text{ K}}}$$

$$S_R = (0.75) \frac{\left(\frac{p_R}{p_B}\right)}{\left(\frac{p_R}{p_B}\right)_{CT=2700 \text{ K}}}. \qquad (5)$$

The resulting power-downconversion efficiencies of the red and green QDS necessary to tune color temperature from 2700 K to 6500 K are shown in Fig. 5(a). In contrast to the changes in absorptions calculated for the first case, the changes in power-downconversion efficiencies here must be substantial. The reason: if absorptions are fixed, the amount of blue light leaking through the QDs is fixed, so all of the change in the power ratios must come from changes in power-downconversion efficiencies.

In this second case, tunability away from the lowest color temperatures requires a decrease in power-downconversion efficiency (essentially a decrease in quantum yield), and a resulting decrease in overall luminous efficacy. And, because the decrease in power-downconversion efficiency and the fraction of blue light that is downconverted are both large, the decrease in overall luminous efficacy is also large. As
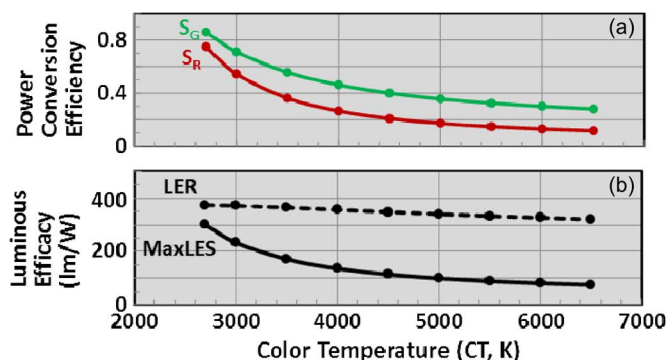
Fig. 5. (a) Power-downconversion efficiencies (at constant absorptions) necessary to achieve the power ratios in Fig. 3(b). We assume that quantum yield is unity and power-downconversion efficiency is determined solely by the Stokes loss at the initial (zero-field) color temperature of 2700 K. The subsequent decrease in power-downconversion efficiency at the higher color temperatures is due to decreases in quantum yield from unity. (b) Luminous efficacy of radiation (LER) associated with the emitted power spectral distribution, and maximum luminous efficacy of source (MaxLES) assuming a 100%-efficient blue LED and, as in (a), power-downconversion efficiencies at 2700 K limited only by the Stokes shifts but at higher color temperatures by decreases in quantum yield.
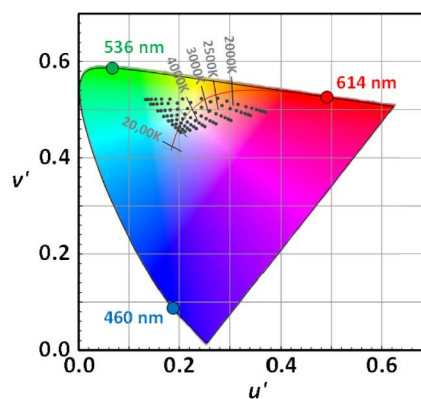

Fig. 6. $u'v'$ chromaticity diagram illustrating the off-Planckian chromaticities (the dotted region overlapping the Planckian) that can be obtained for the power ratio changes necessary to give the on-Planckian range of color temperatures. Also drawn on the diagram are the perimeter wavelengths (460 nm, 536 nm, 614 nm) of the three colors comprising the light source, and various color temperatures along the Planckian.

illustrated in Fig. 5(b), the maximum luminous efficacy of source (MaxLES) achievable (assuming a 100%-efficient blue LED and power-downconversion efficiencies at 2700 K limited only by the Stokes shifts but at higher color temperatures by decreases in quantum yield), decreases rather steeply with color temperature. Some of the decrease in MaxLES is, again, due to the well-known decrease in luminous efficacy of radiation (LER) with increasing color temperature; but most of the decrease is due to decreases in quantum yield.

Thus, this second case is not as ideal as the first case: as color temperature is tuned, color rendering quality is maintained but luminous efficacies are not. However, it may be much easier to implement. As noted above, electric fields cause a spatial charge separation and hence a decrease in emission oscillator strength. This is particularly true for QDs having a rod morphology. The longer radiative lifetime allows intrinsic non-radiaitve processes to compete with luminescence, lowering the quantum yield. Thus, by decreasing the electron-hole overlap, power down efficiencies will change, facilitating this type of tuning in a solid-state, single-chip device.

C. Off-Planckian Tuning

Though our main intent has been to explore how power-ratio tuning can provide color temperature tuning *along* the white-light Planckian, such power-ratio tuning can also tune chromaticities *off* of the white-light Planckian. This can be done by not changing the red-to-blue and green-to-blue power ratios synchronously, as in Fig. 3(b), but instead changing them independently. Indeed, if the two power ratios had ranges the same as indicated in Fig. 3(b) but were varied independently, the resulting color gamut would be that indicated by the black dots in the $u'v'$ chromaticity diagram in Fig. 6. The tunable color gamut is modest compared to that for displays, but is relatively large in terms of perception of hue, and may be large enough for many architectural and special-effects lighting applications.

IV. SUMMARY

We have proposed the possibility of single-chip solid-state lighting with real-time tunable chromaticity based on electrically biasable QD wavelength-downconversion layers integrated with blue LEDs. We discussed a possible architecture for such a solid-state lamp and the chromaticities that could be obtained for given changes in emission wavelength, absorption, or power-downconversion efficiency.

Of the various ways of chromaticity tuning, the best is absorption tuning, as color rendering quality and luminous efficacies are maintained over a wide range of color temperatures. The necessary architecture appears to be difficult to implement in an all-solid-state device, but there may be possibilities for non-all-solid-state devices in which non-spherical QDs with anisotropic absorptions are guests in a liquid-crystal environment.

The two alternative ways of chromaticity tuning are not as ideal.

For wavelength tuning, color rendering quality is difficult to maintain, except over a relatively limited range of color temperature. The trade-off between acceptable color rendering quality and color-temperature tuning range will depend of course on the details of the application.

For power-downconversion-efficiency tuning, luminous efficacy is difficult to maintain, again except over a relatively limited range of color temperature. Of course, given the extremely high efficiencies of solid-state lighting, some decrease in luminous efficacy may be acceptable in order to achieve chromaticity tuning over at least a limited range of color temperature.

We emphasize that, for all three ways of chromaticity tuning, we have focused in this article on quantifying the wavelength shifts, absorption changes, or power-downconversion efficiency changes necessary to achieve particular ranges of color temperature tuning. We have discussed only superficially the practical possibilities for achieving such changes. Our reason is that the magnitude of these shifts or changes will depend strongly on numerous details of the QDs and their configurations and environment: their core-shell compositions (II-VI versus III-V), band-

alignments (Type I or Type II), sizes (few-nm versus many-nm), and especially shapes (spherical versus non-spherical); the wavelengths they are tailored to absorb and emit at; the chemical and dielectric properties of their encapsulants; and the matrix that they are embedded in along with the potential susceptibility of that matrix to electric fields (e.g., orientational effects).

Finally, we note that other semiconductor structures (e.g., quantum wells [40]) might also be interesting to explore for electric-field tunable wavelength downconversion. And alternative tuning schemes, such as pump-intensity-saturable wavelength-downconverters or QD charging [41], might also be worth exploring.

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