Research article

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Energy-saving quality road lighting with colloidal quantum dot nanophosphors

Abstract: Here the first photometric study of road-lighting white light-emitting diodes (WLEDs) integrated with semiconductor colloidal quantum dots (QDs) is reported enabling higher luminance than conventional light sources, specifically in mesopic vision regimes essential to street lighting. Investigating over 100 million designs uncovers that quality road-lighting QD-WLEDs, with a color quality scale and color rendering index ≥85, enables 13–35% higher mesopic luminance than the sources commonly used in street lighting. Furthermore, these QD-WLEDs were shown to be electrically more efficient than conventional sources with power conversion efficiencies ≥16–29%. Considering this fact, an experimental proof-of-concept QD-WLED was demonstrated, which is the first account of QD based color conversion custom designed for street lighting applications. The obtained white LED achieved the targeted mesopic luminance levels in accordance with the road lighting standards of the USA and the UK. These results indicate that road-lighting QD-WLEDs are strongly promising for energy-saving quality road lighting.

Keywords: quantum dots (QDs); light-emitting diodes (LEDs); outdoor lighting; mesopic vision; photometric design.

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1 Introduction

Developing new material systems for lighting technologies has evolved lighting systems and infrastructure from those of primitive gas lamps in the past to the compact fluorescent lamps and light-emitting diodes (LEDs) of today. Most recently, the transformation into the luminaries using LEDs has been making a rapid progress. To date one of the main effort areas for exploiting LED technology has been the indoor lighting because of the large energy consumption of general lighting and the need for high photometric quality of artificial lighting [1, 2]. Another important focus area of LED-based lighting is the road lighting (also known as street lighting), which is equally essential to our modern society for a number of reasons. First, quality road lighting can enhance the safety of roads together with providing comfort for drivers and pedestrians [3]. Furthermore, the number and severity of traffic accidents can be reduced [4] and, as a result, people can be saved from traffic accident injury or death, and financial losses due to traffic accidents can also be minimized. Moreover, night-time traffic activity can be safely increased if proper road lighting is available. Also, in general, the strong need for maximizing energy efficiency (and thus minimizing energy consumption and carbon footprint) motivates increasingly the development of new high-efficiency high-quality light sources including the street lamps as the concerns regarding the energy problem escalate day by day [1, 3].

Designing high quality and high efficiency light sources requires careful spectral design. Because of their low energy consumption, LEDs are good candidates for this purpose. However, broadband-emitting rare earth element based phosphor, used for color conversion in single chip white LEDs (WLEDs), makes the careful tuning of the white light spectrum difficult in addition to the raising concerns regarding their supply security [5]. On the other hand, the green-gap problem along with cost of the driving circuitry limits the use of multi-chip WLED approach [6]. Considering all of these arguments, colloidal semiconductor quantum dots (QDs) step forward because of their narrow emission bandwidths, which allow for careful spectral tuning [7, 8], and their relatively high quantum efficiencies [9]. In recent years, QD based LEDs involving direct charge injection experienced incredible improvements reaching the theoretical limits in terms of efficiency [10]. However, these devices still suffer from the low luminance levels that are not suitable for outdoor lighting applications and strongly decreasing efficiencies at higher currents. Therefore, employing QDs as color convertors on LEDs is more favorable for the general lighting applications.

The spectral requirements of these color converting QD integrated WLEDs (QD-WLEDs) for indoor applications have been deeply studied [7, 11] and efficient devices have already been demonstrated experimentally [8, 12]. In addition to achieving high efficiencies, good color rendition capability became another focus of research leading to QD-WLEDs which can achieve color rendering indices above 90 [13]. Another focus of the research has been the utilization of Cd-free QDs in QD-WLEDs due to environmental concerns [14–16]. Although these devices exhibit successful color rendering capabilities, they lack of high efficiencies in general. Despite the significant number of studies on QD-WLEDs addressing indoor lighting, their application and optimization for the purposes of outdoor lighting have not been investigated at all to date. This particular study aims to fill this gap by first determining the necessary spectral features for efficient outdoor lighting employing color converting QDs followed by the demonstration of a proof-of-concept QD-WLED specifically targeting the road lighting conditions.

Here, we carry out a photometric study of high-quality color-conversion LEDs employing blue LEDs integrated with semiconductor nanophosphors of colloidal QDs that enable higher luminance than those of conventional light sources in mesopic regimes given the road lighting standards in the US and the UK. Having worked with over 100 million designs, we found that QD-WLEDs can supply 15% higher mesopic luminance than cool white fluorescent lamps, 13–22% higher than high pressure sodium lamps, and 33–35% higher than metal halide lamps, while providing a color quality scale and color rendering index ≥85 at the same time. These QD-WLEDs prove to be electrically more efficient than conventional sources provided that their power conversion efficiencies are ≥16–29%, depending on the luminance level standards and compared light sources. Considering these findings, we carried out a proof-of-concept experimental demonstration of the QD-WLED using green, yellow, and red QDs. The luminance exerted by this white LED covered a broad range of visual regimes (scotopic: dark-adapted visual regime where rod photoreceptors are dominantly active, photopic: light adapted visual regime where the cone photoreceptors are responsible for the visual perception, and mesopic: the visual regime of street lighting where rods and cones work together because the lighting level is above the scotopic regime and below the photopic regime) while possessing an electrical efficiency >~29%. This is the first account of a QD-WLED designed for road lighting that is capable of competing existing conventional sources in the mesopic vision regime.

2 Luminance for road lighting conditions

When it comes to the notion of luminance, which is calculated considering the overlap of the radiance of the light source with the human eye sensitivity function and denotes the useful optical radiance for the human eye, the behavior of the photoreceptors within the human retina needs to be elucidated. These photoreceptors, which are responsible for the vision processes, are rods and cones. Rods are sensitive in dark ambience, i.e., they are responsible for the so-called scotopic vision [6]. However, they cannot provide color information; they are easily saturated as the luminance level is increased above a threshold level; and they do not make a significant contribution to the vision in the photopic vision regime. On the other hand, cones are responsible for providing the color information and start to be sensitive above a particular luminance level, i.e., at photopic vision levels for photon-adapted vision. For the luminance levels between these two regimes, which is the so-called mesopic regime, both types of photoreceptors are active. Consequently, the vision sensitivity of human eye in the mesopic regime is different than those in the scotopic and photopic regimes.

Although the existence of these differences were well known and widely accepted, until most recently there has been no consensus on the luminance level boundaries and eye sensitivity function of the mesopic vision regime [17–24]. In 2010, this confusion was addressed by CIE that published a technical report (CIE 191:2010) on a recommended system for mesopic photometry [25]. In CIE 191:2010, the mesopic regime is defined for the luminance levels between 0.005 and 5 cd/m^2, and the eye sensitivity function for the mesopic regime is expressed as a linear combination of the photopic and scotopic eye sensitivity functions depending on the level of photopic luminance. In this letter, we utilize this most recently adapted mesopic photometry system, whose calculation methodology is summarized in the Supplementary Information (SI), for the performance evaluation of QD-WLED based road lighting.

In addition to this mesopic luminance discussion for improved road lighting, another point that deserves attention is the color rendition capabilities of light sources. Raynham and Saksvikrønning reported that a light source with good color rendition capability enhances the visual recognition (e.g. face recognition) [26], which is mainly of interest to pedestrians. However, there is a lot of disagreement about the role of color rendering in facial recognition [27]. Despite the ongoing discussions, we included this feature of sources in our analyses since a successful color rendering may contribute to the street safety, especially for the pedestrians; however, we did not use the color rendition as the final performance metric. Instead, we optimized the spectrum for realizing the highest mesopic luminance provided that a reasonable color rendition is achieved.

3 Computational methodology

Here, we computed the performance of QD-WLEDs for the road lighting and the spectral requirements to realize high luminance in the mesopic vision regime together with a reasonable color rendering performance. In our study, we compared the mesopic luminance performance of the QD-WLED designs with the conventional light sources including the standard daylight source D65, a cool white fluorescent lamp (CWFL), a blackbody radiator at 3000 K, a metal-halide lamp (MH), a high pressure sodium lamp (HPS) and a mercury vapor lamp (MV), whose corresponding emission spectra were obtained from Ref. [28]. Furthermore, we evaluated the color rendition performance of QD-WLEDs using color rendering index (CRI) and color quality scale (CQS), which provides healthier results than CRI for narrow-band emitters [29]. In our calculations, we excluded all the designs having CQS<85 or CRI<85 together with the ones possessing a chromaticity difference (ΔC) larger than 0.0054 to satisfy the good color rendering condition. Imposing this constraint also ensured that the results are compatible with the ANSI NEMA standards [30].

To examine the efficiency of the light sources in the mesopic region, we selected four photopic luminance levels so that the road lighting standards in the USA [31] and the UK [32, 33] are satisfied. We chose 0.50 cd/m^2 for the freeway (0.40–0.60 cd/m^2), collector (0.40–0.80 cd/m^2), and local road lighting (0.30–0.60 cd/m^2) conditions according to the USA, and the link road standards for the UK (0.50–0.75 cd/m^2). We denoted this photopic luminance level as Mesopic 1. The second standard, 0.80 cd/m^2, satisfies the US standards of express way (0.60–1.00 cd/m^2) and major road lighting (0.60–1.20 cd/m^2) and the secondary distributor lighting standard of the UK (0.75–1.50 cd/m^2), which we called Mesopic 2. The third standard, 1.25 cd/m^2, was chosen to fulfill the UK requirements for strategic route (1.00–1.50 cd/m^2), major distributor (1.00–1.50 cd/m^2), and secondary distributor (0.75–1.50 cd/m^2), dubbed here Mesopic 3. Finally, the fourth standard, 1.75 cd/m^2, was selected for motorway lighting standards (1.50–2.00 cd/m^2) in the UK here referred to as Mesopic 4.

Excluding LEDs, CWFL exhibits the highest mesopic luminance at the same optical radiance among all other sources for the scotopic regime and the road lighting standards Mesopic 1 and 2. For Mesopic 3 and 4, and for the photopic regime, HPS takes the lead [12]. Considering these, we applied a threshold for the QD-WLEDs such that only the QD-WLED designs having higher luminance than CWFL and HPS at the same radiance were selected for all six photopic luminance values together with CQS≥85, CRI≥85, and $\Delta C \leq 0.0054$. However, we also paid attention to the fact that HPS and MH are the most widely preferred light sources for street lighting. Therefore, we made use of HPS and MH together with CWFL in our comparative studies. To enhance the computational efficiency, we selected the top hundred spectra, whose design was carried out similar to Refs. [7] and [34], exhibiting the highest mesopic luminance. Further details of the computation method are given in the SI.

4 Results and discussion

In Figure 1A and Table S1 in the SI, the spectral parameters possessing the highest L_{mes} are listed for all four road lighting standards together with the scotopic and photopic vision regimes. Photometric and radiometric properties of the corresponding spectra are summarized in Table S2 in the SI. A careful investigation of Figure 1A and Table S1 reveals that at the very low luminance levels the maximum mesopic luminance is attained when all the color components have similar amplitudes. However, at higher luminance values the content of the red component is very dominant. The decrease in the relative amplitude of the blue emission is also another noteworthy feature at higher photopic luminances. Moreover, the rise in the yellow intensity is another remarkable fact as the luminance level increases. As a result of all these changes,

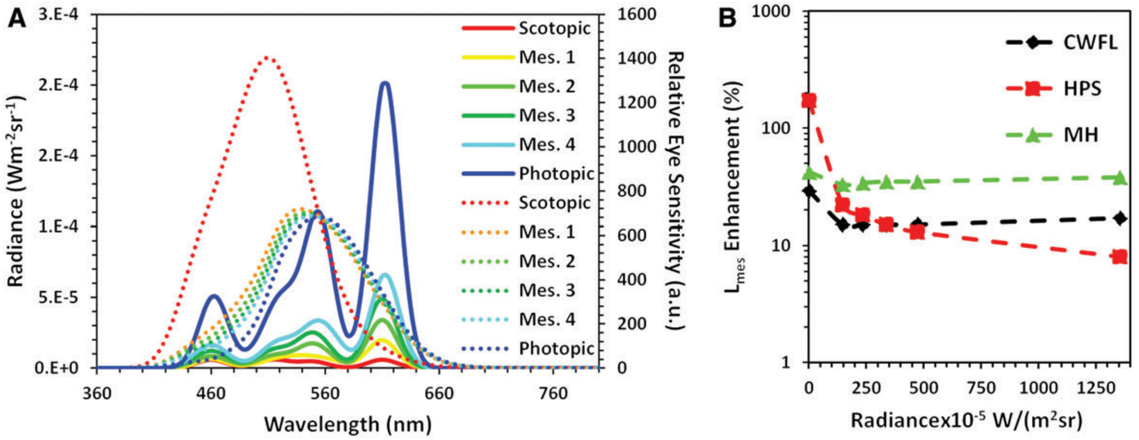

Figure 1 (A) Spectra possessing the highest mesopic luminance (continuous lines) and eye sensitivity function (dashed lines) for the scotopic vision regime, the mesopic road lighting standards 1–4, and photopic vision regime. (B) Enhancement in the mesopic luminance of the QD-WLED designs, which possess the highest mesopic luminance, compared to conventional light sources cool white fluorescent lamp (CWFL), high pressure sodium lamp (HPS), metal halide lamp (MH) as a function of radiance. These values were found by calculating the ratio of the difference in mesopic luminances of the QD-WLEDs and conventional sources to the mesopic luminance of the conventional sources at a given radiance.

the correlated color temperature (CCT), which is related to the shade of the white light, takes lower values that correspond to warmer white.

Another interesting feature of these spectra that possess the highest mesopic luminances is the position of the peak emission wavelengths of the color components. We observe that the blue emission is very close to 460 nm in all of the cases. Additionally, the red component is located at ~610 nm except for the scotopic case. A dedicated discussion on the criticality of wavelength selection is included in the next section. However, at this point this information shows us that the resulting spectra yield a good overlap with the eye sensitivity curves (Figure 1A).

In addition to the discussion of spectral parameters, the photometric properties of the QD-WLED emission deserve attention. Although we did not place any restriction on CCT, we found that the warm white emission (CCT≤4500 K) can be obtained by preserving very high mesopic luminance, CRI, and CQS at the same time. Furthermore, a short discussion on the photopic luminance levels and road lighting intervals is also necessary at this point. The QD-WLED spectra were generated such that their radiances are equal to that of CWFL for the scotopic regime and the mesopic road lighting standards, Mesopic 1 and 2. For the mesopic road lighting standards Mesopic 3 and 4, and the photopic regime, the radiances of the QD-WLEDs were selected equal to that of HPS. Therefore, it could be possible that the generated white LEDs do not remain within the standards mentioned in previous sections. However, the results show that the designed QD-WLEDs are within the standards that we consider in this work; therefore, they are still valid.

Achieving high photometric performance is crucial for high visual quality of the road lighting. This undoubtedly enhances the road safety and contributes to the life quality. However, the overall power conversion efficiency, which can be defined as the ratio of total radiant flux from the device to the supplied electrical power, is another important factor that has to be considered while designing a light source. For this purpose, we calculated the required radiance of the CWFL, HPS, and MH such that the obtained mesopic luminance is equal to the mesopic luminances of QD-WLEDs given in Figure 1A (and Table S1). The results are summarized in Table S3 in the SI. The minimum power conversion efficiency of a QD-WLED ($\eta_{\text{QD-WLED}}$), which is needed for consuming lower electrical energy than the conventional sources CWFL, HPS, and MH while generating the same mesopic luminance, can be calculated using Equation (1):

$$\eta_{\text{QD-WLED}} = \frac{P_{\text{QD-WLED}} \times \eta_{\text{conv}}}{P_{\text{conv}}} \qquad (1)$$

where η_{conv} is the power conversion efficiency of the conventional light source, P_{conv} and $P_{\text{QD-WLED}}$ are the radiances of the conventional source and QD-WLED, respectively. Taking the efficiencies of CWFL as 28%, HPS as 31%, and MH as 24% [34], the minimum required $\eta_{\text{QD-WLED}}$ turns out to be between 21% and 24% when CWFL is employed (Table S4 in the SI). In the case that HPS is preferred for comparison, QD-WLEDs consume less electrical power than HPS while realizing the same mesopic luminance if their power conversion efficiencies become larger than the values presented in Table S4. Finally, the QD-WLEDs are required to possess power conversion efficiencies between 16% and 18% for them to consume less electrical energy than MH lamps while generating the mesopic luminance given in Table S3. Considering that 70% film quantum efficiencies of QDs can be obtained [9], achieving these required power conversion efficiencies is not a big challenge [34].

Another point that is worth mentioning is the efficiency of the luminaires. A luminaire is the system that delivers light to the target illumination volume and may include reflective surfaces as well as lenses and diffusers for mixing and managing the light. The light generated by the sources within the luminary is not delivered to the target volume with 100% efficiency. The typical efficiency remains around 60% for conventional sources [35], and conventional LEDs [36], the rest of the energy is lost as heat. However, the LEDs have the potential to possess higher luminaire efficiencies even up to 90% when more creative luminaire designs are employed [37–41].

Up to this point we compared the performance of the QD-WLEDs proposed in Figure 1A and the conventional sources by fixing the mesopic luminance that the sources are capable of achieving and calculating the required radiances. An alternative approach is to investigate the enhancement of the mesopic luminance when the QD-WLEDs and conventional sources possess the same radiance. When all of these sources have radiances equal to the ones given in Table S2, the QD-WLEDs in Figure 1A are found to exhibit 15–29% higher luminances than CWFL as presented in Figure 1B and summarized in Table S4. This enhancement becomes 8–172% in the case of comparing to HPS and 33–42% in the case of comparing to MH. The results reveal that the use of QD-WLEDs can promise higher mesopic luminances than the conventional sources while consuming less electrical energy.

From an experimental point of view, obtaining a QD-WLED having a specific spectrum, which exactly satisfies the theoretically determined spectral conditions stated in the previous section, is a very challenging task due to uncontrollable deviations from the ideal design during implementation. Therefore, elucidating the strict and flexible parameters is of significant importance in practice. In our study we use the standard deviation to evaluate the criticality of the spectral parameters. Before investigating this, however, it is beneficial to know what would be the standard deviations if we had uniform distribution of these parameters. We may use this information when concluding the importance of various spectral parameters. Our calculations revealed that if we had a uniform distribution of peak emission wavelengths, we would have a standard deviation of 17.1 nm for the blue component and 14.2 nm for the remaining three color components. The full-width at half-maximum would have a standard deviation of 5.6 nm for all four color components in the case of uniform distribution. Finally, the standard deviation of relative amplitudes would be 229/1000.

The average and standard deviations of the peak emission wavelengths of the spectra passing the thresholds are given in Table S5 in the SI and illustrated in Figure 2A. The results indicate that the blue and red peak emission wavelengths should be very carefully adjusted whereas the green and yellow components are not as critical. We found out that obtaining high mesopic luminance requires a blue emission peak located around 460 nm and a red peak around 610 nm. As very low standard deviations show, only small deviations from these average wavelengths are tolerated. However, the choice of green and yellow peak emission wavelengths turned out to be not very critical

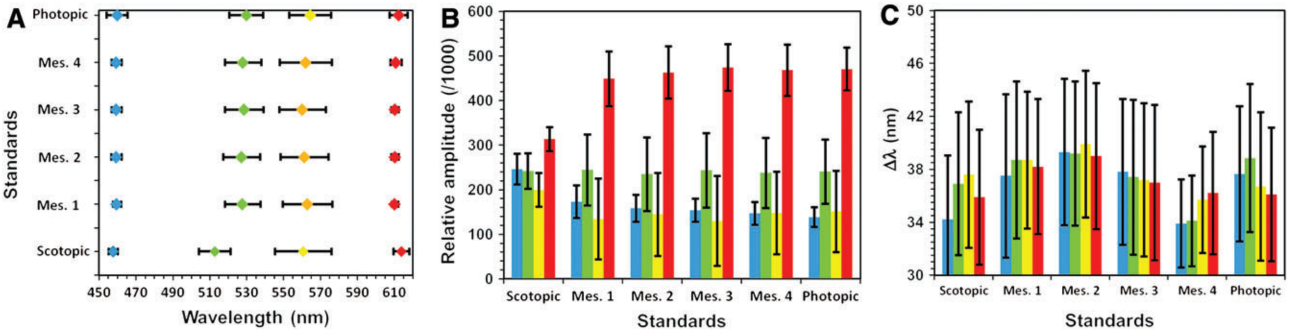

Figure 2 Average and standard deviation (error bars) of (A) peak emission wavelength, (B) relative amplitude, and (C) full-width at half maximum belonging to the spectra passing the thresholds at the simulated luminance levels. The colors indicate the data points belonging to the corresponding color component.

as their very large standard deviations indicate. Therefore, it is safe to choose QDs emitting relatively far from the average values given in Table S5. Another remarkable point is that the choice of the blue wavelength preserves its importance under all luminance conditions whereas the red choice is partially relaxed in the scotopic and photopic vision regimes. This can be due to the fact that the red component gets closer to 620 nm for high efficiency as the luminance level increases towards photopic levels [7].

The average and standard deviations of the relative amplitudes of the spectra passing the thresholds are given in Table S6 in the SI and illustrated in Figure 2B. From these results, we can draw several important conclusions. First of all, for obtaining high luminance in the mesopic regime one has to keep the blue content weak, between 145/1000 and 175/1000. The standard deviations around 25–30/1000 do not allow for a stronger blue content without sacrificing good color rendition and high mesopic luminance. Another interesting feature is that the blue amplitude and its standard deviation decrease as the radiance increases. In addition to the blue content, the red exhibits interesting properties as well. First, the red should be the dominant color component in the spectrum at all the luminance levels we tested. The average amplitude values are located around 330/1000 for the scotopic vision regime, and between 450/1000 and 475/1000 for the four road lighting standards and photopic regime. For the scotopic regime, the low standard deviation around 27/1000 shows that any large deviation will cause a decrease in the photometric performance. Actually, for the scotopic region all the standard deviations of relative amplitudes are very low. Therefore, designs should be strictly based on the values presented in Figure 2B and listed in Table S6. However, at higher luminance levels the standard deviations of the red are in the range of 45/1000–60/1000, which gives some flexibility during the spectral designs. When it comes to the green and yellow components, we observe that the green takes intermediate values whose average intensity is almost the same at all the radiances. On the other hand, the yellow content remains very low, even lower than the blue component in some cases. However, both of these color components have very large standard deviations, which increase the freedom of designers in adjusting their weights.

The average and standard deviations of the full-width at half-maximum belonging to the spectra passing the thresholds are given in Table S7 in the SI and the results are illustrated in Figure 2C. Here we observe that the blue, green, and yellow color components have similar average values and similar standard deviations regardless of the luminance level. Moreover, the resulting standard deviations (around 5–6 nm) are very close to the case of uniform assumption (5.62 nm). Therefore, we conclude that the designer has a high flexibility for selecting the full-width at half-maximum values of these emitters. The only critical color component turns out to be the red one. In that case the full-width at half-maximum values are the lowest ones except the scotopic case. More importantly, for the luminance standards of road lighting the standard deviations are narrower than the others. Therefore, the full-width at half-maximum selection only for the red component should be carefully selected. It should be narrow (34–35 nm) and large deviations are not tolerated at the appropriate luminance levels of road lighting.

5 Experimental demonstration of a QD-WLED designed for road lighting

Within the framework of this study, we also carried out a proof of concept experimental demonstration of a QD integrated white LED. First, green, yellow, and red emitting QDs are synthesized. The green- and yellow-emitting QDs, which are synthesized according to Ref. [42], acquire CdSe/CdS/ZnS core/graded-shell architecture. Details of the synthesis procedure can be found in SI. The synthesized QDs emit at 531 and 552 nm, and the corresponding full-width at half maximum values are 41 and 36 nm. Orange-red emitting CdSe/CdS core/shell QDs are synthesized according to Ref. [43]. These QDs acquire a peak emission wavelength of 604 nm with a full-width at half maximum of 33 nm. Their photoluminescence and absorption spectra in hexane are presented in Figure 3A along with a photograph under ultraviolet light illumination (inset). The QD-WLED was prepared with a method similar to Ref. [8] employing an Avago ASMT MB00 Blue LED emitting at 460 nm together with 55.7, 28.8, and 59.2 μg of green, yellow, and red QDs, respectively.

The prepared QD-WLEDs were driven at varying current levels from 10 to 150 mA. The corresponding emission spectra are presented in Figure 3B. The emission spectra and luminance were measured by using an Ocean Optics Maya 2000 spectrometer and Newport optical power meter. The spectra presented in Figure 3B reveal that especially for the high current cases the blue content in the white LED spectrum is stronger than it is intended. This is related to the density of the QDs in the film; however, the challenge here is keeping the quantum efficiency of the QDs still at a higher level when the QDs are dense in film.

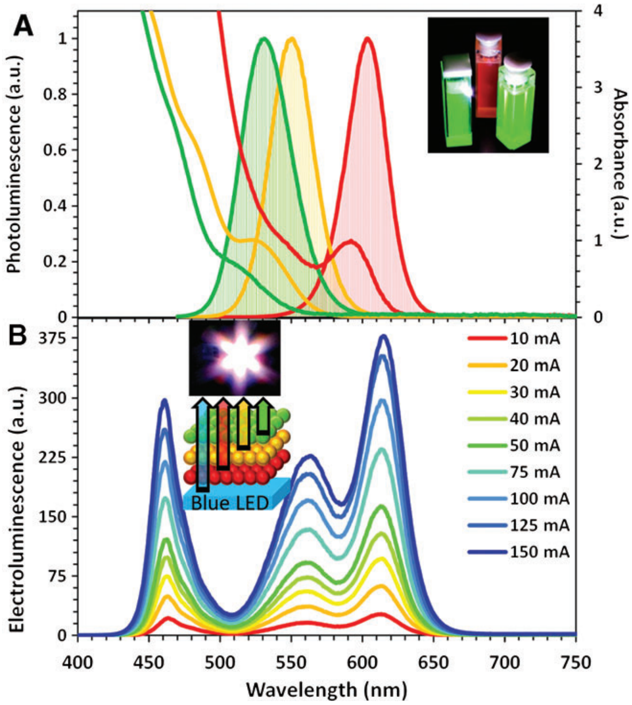

Figure 3 (A) Photoluminescence and absorption spectra of the quantum dots in hexane along with the photographs of QDs under UV illumination. (B) The emission spectrum of the QD-WLEDs at various current levels and (inset) the illustration and real photograph of the QD-WLED comprising of a blue LED pumping green, yellow, and red QDs.

For the luminaries requiring higher currents, this challenge needs to be overcome possibly through the development of new encapsulation techniques.

The luminance levels of the QD-WLED were calculated according to the photopic and associated mesopic eye sensitivity functions. The results are presented in Figure 4 along with the calculated efficiency. The exhibited luminance levels cover a broad range of photopic and mesopic luminance levels, which include the luminance levels for outdoor lighting aimed in this particular study. The spectra of the QD-WLED acquire a better spectral overlap with the mesopic eye sensitivity function compared to its photopic counterpart resulting in a higher perceived luminance under mesopic conditions. The efficiency levels remaining >~29% show that these proof-of concept devices might be efficient competitors of conventional light sources by offering high luminance and good color quality.

6 Conclusions

In conclusion, here we have showed that, at the mesopic light levels while emitting at the same radiance, QD-WLEDs can provide ca. 15% higher luminance than the CWFL, 13–22% than HPS, and 33–35% than MH light sources used for road lighting, thanks to the narrow emission bands of the QD-WLEDs that are strategically placed with the right wavelength combinations. Moreover, we found the necessary spectral parameters for achieving this high performance at four different luminance levels chosen in accordance with the road lighting standards of the US and the UK, and in the scotopic and photopic vision regimes. Additionally, we demonstrated that these high-quality QD-WLEDs are also electrically more efficient than CWFL, HPS, and MH as long as their power conversion efficiencies are kept above 24%, 26–28%, and 18%, respectively, in the mesopic regime, which are achievable levels given the current efficiency levels.

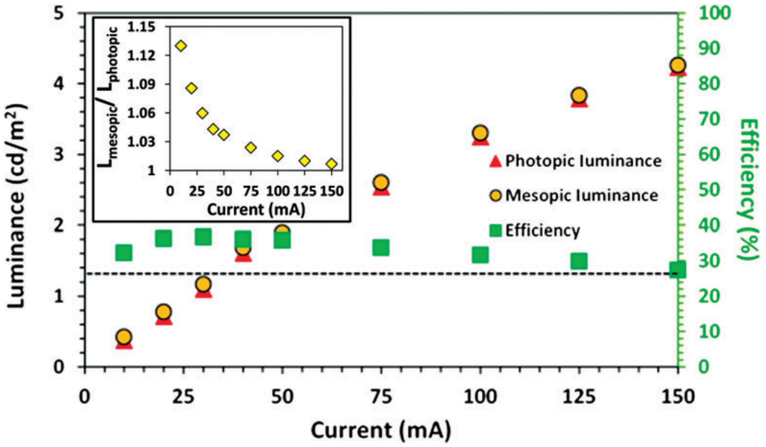

Figure 4 Experimental demonstration of the photopic and mesopic luminance, and the efficiency of the fabricated QD-WLED along with the ratio of mesopic and photopic luminances at the corresponding current levels (inset).

These results led us to a proof-of-concept experimental demonstration of QD-WLEDs using green, yellow, and red QDs. The achieved luminance values covered a broad visual regime range while realizing an electrical efficiency of >~29%. As a result, here we conclude that replacing the conventional sources with these devices can be cost effective in terms of operational costs in addition to the generation of higher mesopic luminances. Given the potentially high performance of QD based color conversion, addressing the stability issues is essential. All in all, these results suggest that quantum dot integrated white LEDs make strong candidates for replacing conventional light sources in the future as they enhance the vision quality in the road lighting in addition to energy saving. Therefore, they offer the potential to enable safer efficient lighting on the roads.

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Graphical abstract

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Energy-saving quality road lighting with colloidal quantum dot nanophosphors

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Photometric design of quantum dot integrated white light-emitting diodes (QD-WLEDs) is carried out for road lighting for the first time. QD-WLEDs are shown to enable 13–35% higher luminance than conventional light sources commonly used for the road lighting and necessary spectral conditions are revealed to realize efficient road lighting. Moreover, the first account of the experimental implementation employing a QD-WLED specifically designed for road lighting is carried out.

Keywords: quantum dots (QDs); light-emitting diodes (LEDs); outdoor lighting; mesopic vision; photometric design.