High-Luminance QD-LED Device With Digital and Dynamic Lighting Functions for Efficient Automotive Systems

Juan José Santaella, S. Rodríguez-Bolívar, L. Puga-Pedregosa, A. González-Rico, M. Marín-González, and Francisco Manuel Gómez-Campos

***Abstract*—This work reports the design of a 60-segment photoluminescence quantum dot light emitting device (QD-LED) for automotive lighting systems. The QD-LED device was fabricated using a quantum dot film (QDF), incorporating two kinds of quantum dots (QDs) synthesized to emit at 531 nm (green) and 624 nm (red). When the QDF is excited with blue wavelength at 465 nm, a white color output is obtained. Likewise, by using different color filters, all the automotive lighting functions (interior and exterior) can be achieved. In addition, an electronic control module, based on the state-of-the-art multichannel automotive lighting emitting diode (LED) drivers, was specifically designed to control each segment individually to enable the possibility of external digital communication with the vehicle surroundings. That is key to develop the autonomous vehicle by incorporating what is known as car-to-X communication, used to transmit information to other vehicles and road users through light. Furthermore, this work is remarkable due to the low power consumption of the QD-LED device designed, which implies a high electrical efficiency, something critical for the electrical vehicle development. Besides, figures of merit and performance indicators are measured, offering promising values to use this nanotechnology in the next future of the vehicle transportation lighting systems.**

***Index Terms*—Quantum dots, QD-LED, automotive lighting systems, nanotechnology, digital communication, electrical vehicle, autonomous vehicle.**

I. Introduction

NOWADAYS, the automotive industry is undergoing some technological and social revolutions that are shaping the greatest ever upheaval in transportation [1]. For the automotive sector, these forces are giving rise to three disruptive technological trends: electrification, autonomous vehicles, and digital mobility [2], [3]. As well as being simultaneous, all three revolutions are extremely fast-paced [1].

Therefore, with the increase of electric motors to the detriment of diesel engines, the vehicles of the future will be much more environmentally friendly thanks to electrification. Likewise, with the autonomous revolution, vehicles will be connected and the driver will delegate more tasks for the car to handle complex traffic situations [1], [3], [4]. Finally, the digital revolution is paving the way for new forms of mobility, implying the vehicle integration of new functions of communication with other vehicles and road environment [1]–[4]. Thus, as reported by Aschenbroich [1], the revolutions currently taking place in the automotive industry are going to disrupt usage patterns so dramatically that it is difficult to know exactly how people will be using cars tomorrow by blurring the distinction between individual and collective transportation.

In the frame of these revolutions, automotive lighting systems play an important role. Thus, light emitting devices (LEDs) are replacing the use of halogen lamps in rear and headlamps [5], [6]. Those solid-state devices offer a low energy consumption and a long useful life, which is key in the eventual integration in the electric vehicle, contributing therefore to the carbon footprint reduction. Moreover, as indicated by Kruppa *et al.* [7], [8], customization and car-to-X communication is a desirable feature in rearlamp lighting systems since digital information can be shared with the vehicle surroundings, which is vital for the final autonomous vehicle implementation and the desired digital mobility introduced above.

However, as style is also a key parameter for automotive lighting systems, the current and future trend in the automotive world is to achieve even greater lighting surfaces with flexible features and shapes in three-dimensions (3D) as shown in Fig. 1.

Nevertheless, the present LED technology used in the automotive field is formed by discrete devices of point light sources. Thus, it is quite complex and expensive to achieve large lighting surfaces using the LED devices available in the market. In addition, the current solution is based on the use of optical diffusers to scatter the light in combination with single-color emitting LEDs (for example red LEDs for TAIL or STOP lighting functions; amber or yellow for TURN INDICATOR). Nevertheless, a dramatic system-based optical efficacy loss happens by using those optical diffusers. In this manner, in order to improve the

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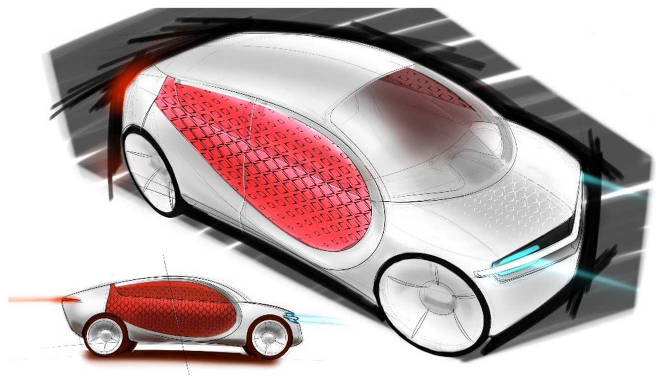

Fig. 1. Vehicle integrating large and homogeneous lighting surfaces. Designed by Valeo ® for this work.

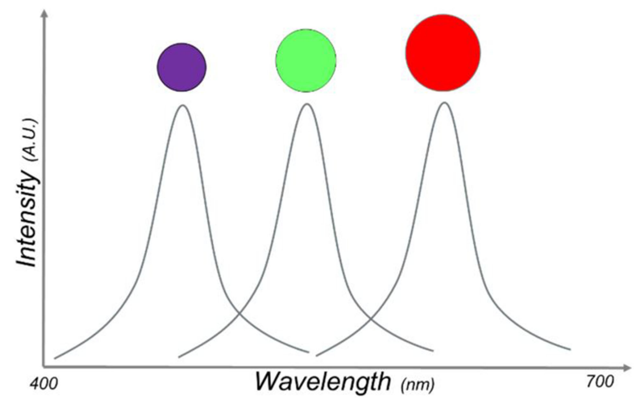

Fig. 2. The quantum confinement allows adjusting the emission wavelength by controlling the size of the quantum dot. The larger the quantum dot, the longer the emitted photon wavelength. The diameter of the blue QD (d_{blue}) is smaller than the green and red one i.e. $d_{blue} < d_{green} < d_{red}$.

homogeneity, it is necessary to increase the diffuser material thickness [7], [8], which leads to a low-efficiency optical systems as a whole.

A real and validated alternative to cover these technological needs described above is based on the use of OLEDs (organic LEDs) [6]. However, although the current automotive OLED complies with the car manufacturer requirements, the intrinsic instability of those optoeletronic devices due to the organic nature makes them unreliable when subjected to large temperature differences such as those in the automotive industry with ranges from -40 °C to 105 °C. Likewise, degradation of the organic layers might occur, reducing drastically the lifetime of OLEDs [9] when compared with other consumer OLED electronic devices, where environmental conditions are more friendly than in the automotive field. Indeed, the physical and chemical stability of the organic thin films is behind the degradation of the OLED device [10]. Consequently, the effect of the degradation of the OLED during operation occurs in three different modes i.e. decay of luminance, voltage increase in the constant-current mode and growth of non-emissive areas (dark spots) [10], [11].

Therefore, to tackle degradation issues for OLED, complex manufacturing processes must be put in place, increasing the final cost of the OLED to be used in the automotive environment. Hence, the possibility to find new potential lighting alternatives for the automotive industry to support and complement the use of the already validated OLED technology shapes the motivation of this work.

Nowadays, quantum dots (QDs) could solve the issues described above effectively in the automotive field. QDs are nanocrystal semiconductors where electrons are confined in a region of space of nanometric dimensions. This implies the existence of a quantum confinement in the three dimensions of space. A particular kind of QDs, the colloidal quantum dots (CQD), are of interest for our purposes. The main characteristics exhibited by these nanostructures due to the confinement are [12]:

1) Diameters typically in the range [2, 50] nm.

2) The density of states (DOS) becomes abrupt thus behaving as "artificial atoms" or superatoms.

3) The energy spectrum of both absorption and emission becomes discrete.

4) The optical and electronic properties can be adjusted by controlling the size of the nanocrystals as shown in Fig. 2.

Specifically, LED lighting devices based on quantum dots (quantum dot LEDs), known by their acronym QD-LED, offer a promising future as a new generation of lighting devices due mainly to three factors [13]:

a) Purity of color: Narrow emission bands that can be spectrally positioned by controlling the size of the nanocrystal during its synthesis.

b) Processability: Methods of synthesis through colloidal solutions that allow the use of low cost deposition techniques on large surfaces, both rigid and flexible.

c) Stability: Composed from inorganic materials, the quantum dot LEDs can be designed to withstand wide temperature profiles.

Furthermore, there are two physical mechanisms from which it is possible to take advantage of QDs when it comes to light-emitting devices. First, when an electrical current is used to excite QDs, electroluminescence (EL) devices are obtained. Secondly, if that QD excitation comes from a higher energy radiation than the one defined by the QD layer, photoluminescence (PL) phenomenon is considered. Thereby, after analyzing the photometrical values required by the different lighting functions in the automotive field, it can be stated that photoluminescent QD-LED devices could take over in a short-term timing. Nevertheless, it will be necessary to wait more development time and thinking in a medium/long term to introduce electroluminescent QLED devices in the automotive field.

Besides, the term Quantum Dot Film (QDF) will be used to particular devices where QDs are embedded in isolated substrate films (rigid or flexible) and excited with UV or deep blue wavelength as shown in Fig. 3.

II. Materials and Methods

A. QD-LED Design

Taking into account the two physical phenomena that could excite the QDs and the current status of this nanotechnology according to the literature, photoluminescence mechanism was

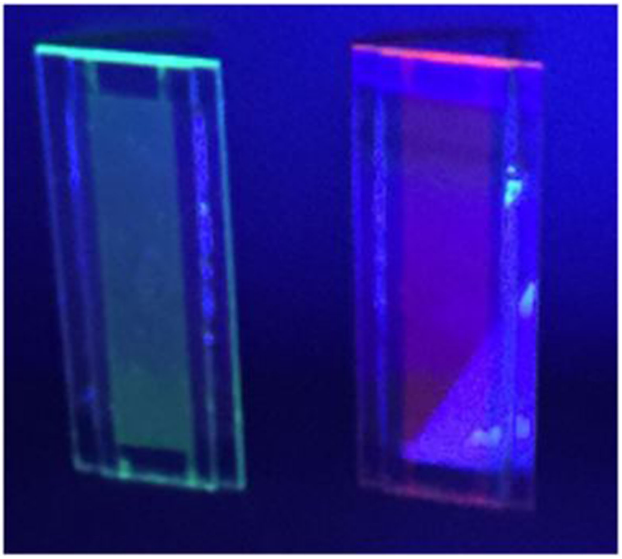

Fig. 3. Example of experimental QDF fabricated in this work incorporating red and green QDs in two different substrates: typical PL mechanism when exciting QDs embedded in a substrate with UV or deep blue light.

Fig. 4. Dynamic photoluminescence QD-LED application for automotive lighting systems. Designed for this work.

selected to conform the QD-LED optoelectronic device. Thus, QDF sheets, including quantum dots as main nanoparticles to be excited by a higher energy radiation, were used as main part of the QD-LED automotive demonstrator that was designed. The objective of this demonstrator is to create a specific model, which could be integrated in a real automotive product. Particularly, a 60-triangular-segment dynamic mockup was designed and physically implemented. Thereby, a mechanical, optical and electronics design was carried out to integrate the QDF sheets in a specific QD-LED automotive lighting application as shown in Fig. 4.

B. Quantum Dot Film

The whole design spins around the QDF sheets acquired commercially from Nanjing Bready Electronics®. These kinds of QDF incorporate QDs with low full width at half maximum (FWHM) values, which is closely related with the purity of the

TABLE I
OPTICAL SPECIFICATIONS OF QDF USED FROM NANJING BREADY ELECTRONICS®[14]

OPTICAL DATA	VALUE	UNIT
Transmittance	≥ 50	%
Haze	≥ 80	%
Luminance Uniformity	≥ 70	%
Red peak wavelength	624	nm
FWHM red	≤ 25	nm
Green peak wavelength	531	nm
FWHM green	≤ 30	nm

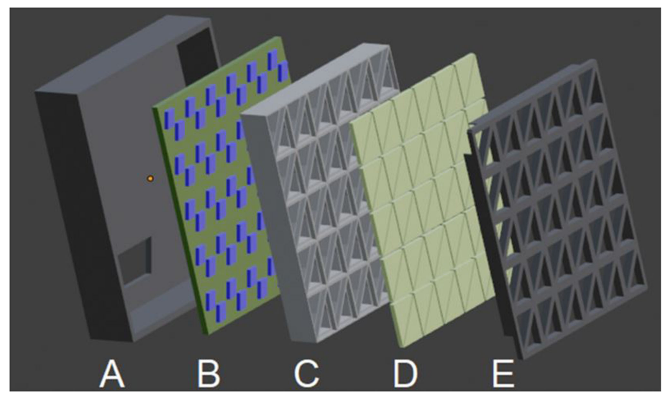

Fig. 5. Exploded view of the experimental QD-LED device assembled. A) Case, B) Blue LEDs, C) Optical system, D) QDF, E) Light cover. Designed for this work.

final output color. Moreover, the active material offers a good transmittance, which is important for the whole system efficiency and high values of uniformity, something really attractive from an automotive lighting perspective. The main technical features of the QDF used are presented in Table I.

As it can be found in the QDF datasheet, these quantum dot films absorb the blue light in the backlight and red and green wavelengths are emitted, which are eventually mixed with part of the blue light to form the final white light.Considering the haze parameter from Table I, it is possible to anticipate a good light scattering created by the quantum dots incorporated, which will lead to a great surface light homogeneity. Therefore, thanks to these QDF, it is possible to generate white light spectrally composed by blue, green and red wavelengths. This white light could be used to make automotive lighting functions like Daytime Running Light (DRL), Position Light (PL) or it can be just color-filtered afterwards to perform Taillighting or STOP (break) applications.

C. Mechanical-Optical Design

GPL or free computer-aided design (CAD) software Blender® was used to build up the mechanical-optical implementation. Thus, different mechanical parts to integrate the 60 triangular-shape segments were drawn as shown in Fig. 5.

As it can be seen from Fig. 5, a first mechanical case, which will support the whole QD-LED device, contains in first place the electronics printed circuit board (PCB). That PCB incorporates the blue LEDs centered-positioned to act as main source to excite

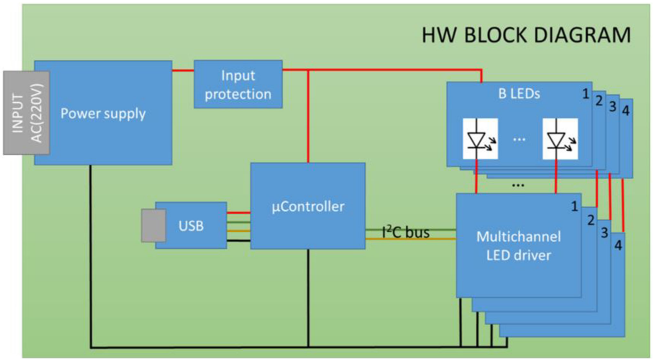

Fig. 6. HW block diagram designed for this work.

the red and green quantum dots included in the QDF layer. To optically guide the blue light to the specific segments formed in the QDF, a system designed by optical cavities is located in between. Finally, a light cover to adjust the output light from the QDF photolumiscence layer is placed on the top of the QD-LED device. Optionally, a color filter made out of plexiglass (PMMA) can be positioned after the light cover part to filter red wavelength. Moreover, in order to physically support the QD-LED device and to integrate all the electronics to control the individual blue LEDs, a mechanical base was designed as depicted in Fig. 4. Eventually, mechanical and optical parts were 3D printed, post processed and assembled to fit the QD-LED device and the electronics presented below.

D. Electronics Design

The electronics part is the core of the dynamic motion of the QD-LED demonstrator. It is composed by two different related developments i.e. hardware (HW) and software (SW). These two implementations are briefly described in the following.

1) Hardware: Fig. 6 shows the HW block diagram of the electronics design. An AC/DC conversion block is placed firstly to regulate the voltage input to around 6 V. This voltage supplies the linear multichannel driver topology controlled by a microcontroller, which is in charge to activate the individual driver channels throughout I ^{2} C bus communication to set an specific current to the blue LEDs. The system is also prepared to be programmed by USB interface.

Finally, the mechatronics integration of the electronics in the mechanical base is carried out as shown in Fig. 7.

2) Software: The SW is uploaded to the microcontroller device throughout over-the-air programming (OTA) thanks to the capability of the microcontroller to set a WIFI link. Thus, using a .csv file (generated by Matlab® code) the dynamic scenarios to individually control the 60 segments in the QD-LED device can be set. In addition, an HTML coded application was created as QD-LED device interface. In this application, both the current passing through the LED and the duty cycle of the latter can be accurately set. Besides, the dynamic motion or preset animations can be selected as well (once the. csv file is uploaded into the microcontroller memory).

TABLE II
MINIMUM AND MAXIMUM LUMINOUS INTENSITY AND FLUX REQUIREMENTS BASED ON THE EUROPEAN COMMISSION STANDARD (ECE) AUTOMOTIVE REGULATIONS [15]–[17]

SIGNALING FUNCTION	COLOR	MAX I_V(cd)	MIN I_V(cd)
STOP	Red	260	60
TAIL	Red	17	4
TURN INDICATOR	Amber	500	50
FOG	Red	300	150
REVERSE	White	300	80
DRL	White	1200	400

TABLE III
BLUE LED ELECTRICAL/OPTICAL CHARACTERISTICS FROM DATASHEET [18]

BLUE LED (datasheet)	SYMBOL	I_F(mA)	TYP	UNIT
Forward Voltage	V_F	100	2.9	V
Luminous Flux	Φ_V	100	8.7	lm
Chromaticity Coordinate	x	100	0.133	-
Chromaticity Coordinate	y	100	0.075	-
Thermal Resistance	$R_{\theta JS}$	-	20	°C/W

E. Scientific Instrumentation

Once the QD-LED automotive application was built-up using the QDF described, the performance of the final device was assessed. That evaluation is based on the regulation automotive photometric values highlighted in Table II.

Therefore, the general objective is to make a comparison between the boundary photometric conditions around automotive applications and the performance that photoluminescence-based QD-LED can offer to the transport field. Thereby, the QD-LED characterization was performed by varying the blue LED current in a dynamic range to obtain the measurements values desired at each layer step, i.e. the blue LED source, the QDF layer and the final output after red-filtered with a PMMA part.

The specific laboratory techniques and instrumentation used for QD-LED device characterization were an optical spectrometer to obtain the emission spectrum and the luminous flux, a photometer to measure the light intensity and the luminance and a source meter to calculate the luminous efficacy of the lighting sources.

III. RESULTS

As described above, each layer of the QD-LED device was characterized.

A. Blue Light Source

The commercial LED used as blue main source is the NE2B757GT from Nichia® optoelectronics. The main parameters of that LED shown in Table III are extracted from the technical datasheet.

Likewise, in order to experimentally characterize the blue LED used, different currents at ambient temperature (25 °C) were set through it to extract the following data in Table IV by using the Feasa® optical spectrometer.

As it can be seen, the values obtained experimentally are in line with the ones extracted from the datasheet of the blue LED @I_F=100 mA i.e. 8.7 lm (datasheet) vs 7.35 lm (measured),

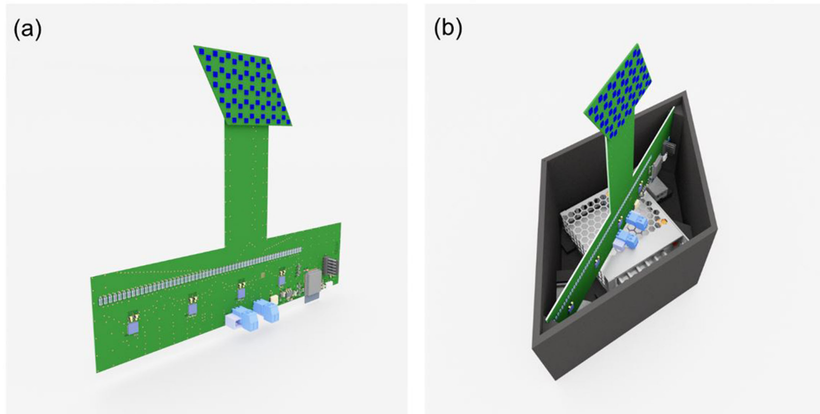

Fig. 7. Mechatronics integration designed for this work. (a) Electronics + PCB. (b) Mech base with power supply.

TABLE IV
EXPERIMENTAL CHARACTERIZATION OF BLUE LED USED AS MAIN SOURCE

BLUE LED (measured)	SYMBOL	I_F(mA)	VALUE	UNIT
Radiant Power	Φ_E	25	29.1	mW
		52	63.9	
		75	90.6	
		90	106.6	
		100	114.5	
Luminous Flux	Φ_V	25	1.99	lm
		52	4.35	
		75	5.98	
		90	6.98	
		100	7.35	

TABLE V
EXPERIMENTAL CHARACTERIZATION OF QDF LAYER

QDF (measured)	SYMBOL	I_F(mA)	VALUE	UNIT
Radiant Power	Φ_E	25	2.9	mW
		52	6.6	
		75	9.7	
		90	11.6	
		100	12.8	
Luminous Flux	Φ_V	25	0.58	lm
		52	1.29	
		75	1.92	
		90	2.29	
		100	2.54	
Chromaticity Coordinate	(x,y)	25	(0.206,0.199)	-
		52	(0.205,0.200)	
		75	(0.207,0.202)	
		90	(0.208,0.202)	
		100	(0.208,0.202)	
Dominant wavelength	λ_d	25	476.4	nm
		52	476.1	
		75	476.0	
		90	475.9	
		100	475.9	
Peak wavelength	λ_p	25	465.9	nm
		52	465.4	
		75	465.2	
		90	465.1	
		100	464.9	

which is a value that falls within the total flux bin range [6.4, 12.7] lm of that LED, deducing that we are in the flux bin P2 range for that reference [18]: [6.4, 7.6] lm. Thus, they will be used to calculate specific figures of merit.

B. Quantum Dot Film

Once the blue LED source had been analyzed, the quantum dot layer or QDF was characterized. Following the same previous strategy, different currents at ambient temperature (25 °C) were set through the blue LEDs to extract the data in Table V from the spectrometer instrument, just after the QDF layer. This characterization is important so as to reach the final objective of comparing in Section III-C the results extracted from different optoelectronic devices like automotive OLEDs.

Moreover, the optical spectrum is shown in Fig. 8 at a forward current I_F=100 mA. As expected, two new spectral components appear i.e. green and red contributions, due to the quantum dots incorporated in the QDF. Those results are in line with the QDF datasheet specifications from Table I, where green peak wavelength is found at 531 nm and red peak one is positioned at 624 nm.

Nevertheless, as the QDF is a commercially acquired layer and it has not been specifically designed for our automotive purpose, it can be observed that the blue contribution to the whole spectrum is much larger than the green and red ones.

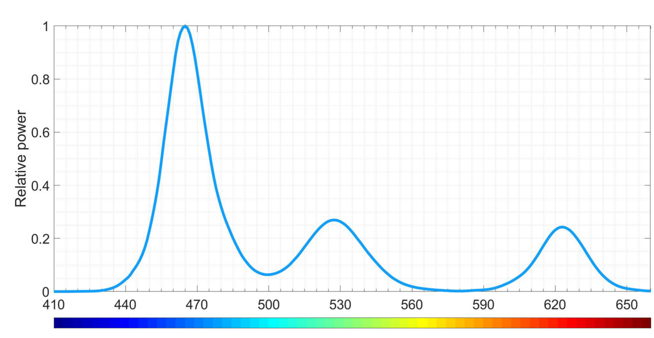

Fig. 8. QDF optical spectrum @I_F=100 mA by using the Feasa® optical spectrometer.

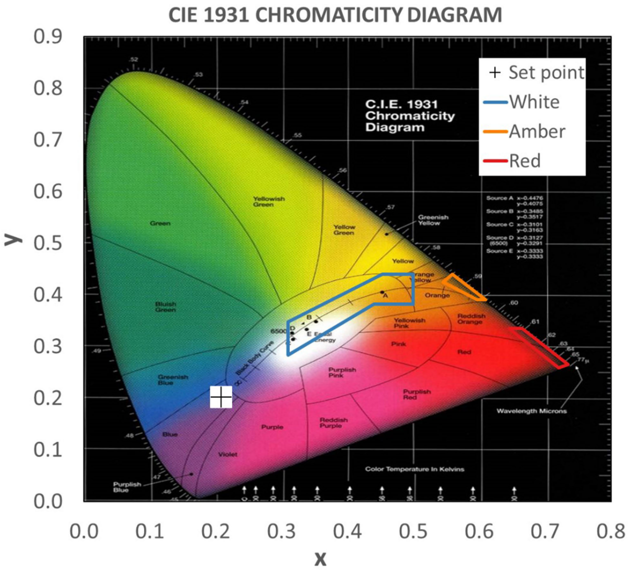

Fig. 9. QDF CIE diagram created @I_F=100 mA. Set point is out of automotive white area. Blue, orange and red highlighted polygons indicate the allowed automotive points for white, amber and red colors from a legal aspect. The cross-shaped set-point shows the output color of the QDF, which is out of automotive white area [17].

Thus, the output color after the QDF is not utterly white, strictly speaking, but bluish instead.

In fact, if we focus now on the output chromaticity coordinates and particularly on the color automotive homologation areas defined in the International Commission on Illumination (CIE) space and represented in Fig. 9, where chromatic colors are specified with the so-called x and y coordinates, it is possible to conclude that some actions have to be put in place to consider the QDF selected as an automotive wavelength conversion layer.

Therefore, our proposal to obtain a white color inside the homologation area for automotive field is twofold. Firstly, by optimizing the density and quantum yield (QY) of green and red quantum dots in the QDF, the spectral contribution of green and red could be increased, taking into account that increasing the density of QDs too much could lead to re-absorption effects, which could eventually mean a reduction of the system efficiency [19]–[21]. And secondly, we can compensate the contribution of blue color to the final output spectrum by adding some specific blue anti-transmission film (BATF) to improve the color-conversion efficiency (CCE) and the stability of the QDF [22].

Besides, and going on with the automotive homologation photometrical values, the luminous intensity (I_V) was also measured by using the photometer from LMK®, taking into account the whole QD-LED device segments, and represented in Fig. 10 for some current configuration and compared with the automotive regulation data from Table II.

Thereby, by anticipating the lineal behaviour of the system given by Fig. 10 and just to highlight the potential use of blue LED source + QDF, without taking into account the color points and only the luminous intensity quantities from Table II, we could imagine different possible automotive lighting scenarios

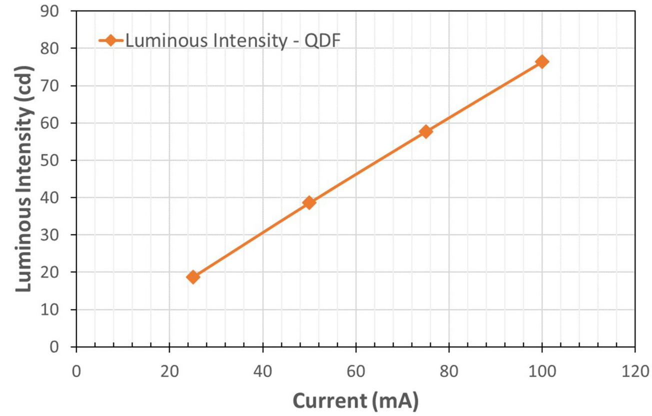

Fig. 10. Luminous intensity vs Current on the QDF layer. The lines are a guide for the eye.

once the whole system was optimized to meet the requirements for automotive applications. Thus, lighting functions like STOP (I_{Vmin}=60 cd), TAIL (I_{Vmin}=4 cd), TURN INDICATOR (I_{Vmin}=50 cd) or even REVERSE (I_{Vmin}=80 cd) would fit the performance given by the QDF and could be theoretically implemented in an automotive environment. However, other lighting functions like DRL (I_{Vmin}=400 cd) or FOG (I_{Vmin}=150 cd) are far from the actual QDF performance. Although again, by designing a specific automotive QDF, the whole efficiency system could be increased and higher values of luminous intensity might be targeted.

On the other hand, it is possible to define some performance indicators like the luminous efficacy (lm/W) and the current efficiency (cd/A) as defined in (1) and (2) respectively.

$$\eta = \frac{\Phi_V}{I_F V_F} \tag{1}$$

where Φ_V is the luminous flux, I_F is the forward current throughout the blue LED and V_F is the forward voltage of the blue LED (2.9 V typical from Table III).

$$\eta_c = \frac{I_V}{n I_F} \tag{2}$$

where I_V is the luminous intensity, I_F is the forward current throughout the blue LED and n is the number of individual segments or blue LEDs and equal to 60 in our case.

Thus, using the first blue LED layer as electroluminescent layer (to try to compare our photoluminescence device with an electroluminescent one), the latter indicators are shown in Figs. 11 and 12.

These QDF indicators values, specifically the luminous efficacy, could be higher in reality due to two main factors. Firstly, the light leakage due to the QD-LED device built up process. Since it has been a proof of concept mockup, several mechanical improvements could be made to avoid any leakage of light. And secondly, the instrumentation used, i.e. the optical spectrometer and particularly the integrated sphere incorporated to collect the optical radiation cannot take all the output light from the QDF surface accurately.

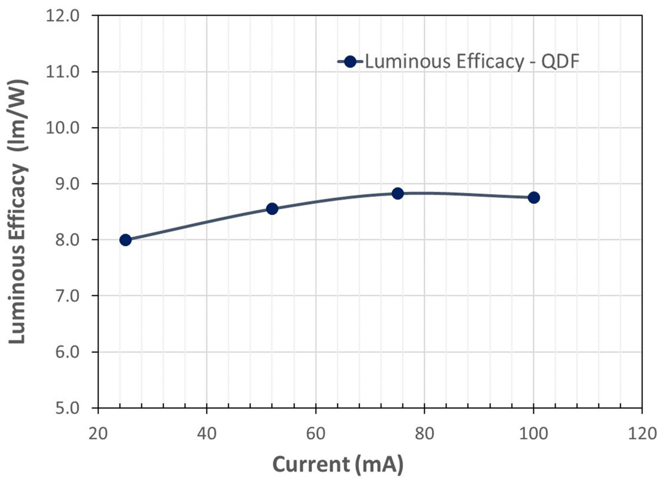

Fig. 11. QDF performance indicators. Luminous efficacy was measured at individual or segment level of the QD-LED device. Moreover, for luminous efficacy, the typical V_F=2.9 V from Table III is used in all cases as approximation to calculate the power in the blue source.

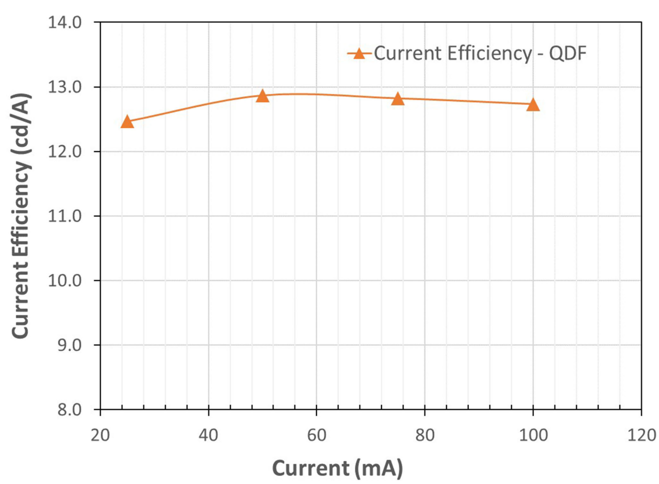

Fig. 12. QDF performance indicators. Current efficiency was measured at individual or segment level of the QD-LED device. Moreover, for luminous efficacy, the typical V_F=2.9 V from Table III is used in all cases as approximation to calculate the power in the blue source.

Furthermore, although it is not specified in the QDF datasheet, an increase in the quantum yield of the quantum dots used could result in a global efficiency increase as well. To do so, both the materials and the synthetization process should be thoroughly analyzed. In addition, although it is out of the scope of this research, the reliability of the QDs and the QDF is something to take into account to comply with an automotive environment. Thus, to improve the stability of QDs under harsh conditions, such as exposure to humidity, UV or thermal heating, different approaches of controlling the structure of the shell, ligands and overcoating might be followed to avoid degradation as described in [23]. Thereby, some reliability data of the QDF used are shown in Table VI extracted from [14], showing encouraging values for automotive field applications in the future.

Moreover, it seems that there is a saturation in the blue LED used as main source when it is driven at high current (maximum

TABLE VI
AGING TESTS PERFORMED ON THE QDF LAYER USED IN THIS WORK

Test	Conditions	Parameter	Result*
Temperature + Humidity	60 ºC, 90% RH** ,1000 Hr	Color Shift	$\leq \pm 0.008$
		Luminance Shift	$\leq \pm 10\%$
		Edge-Ingress	$\leq$ 1mm
Thermal Shock	-20 ºC, 0.5 Hr 70 ºC, 0.5Hr ,500 times	Color Shift	$\leq \pm 0.008$
		Luminance Shift	$\leq \pm 10\%$
		Edge-Ingress	$\leq$ 1mm
High Temperature	85 ºC, 500 Hr	Color Shift	$\leq \pm 0.008$
		Luminance Shift	$\leq \pm 10\%$
		Edge-Ingress	$\leq$ 1mm
Bright light	450 nm, 300 mW/cm^2 60 ºC, 500 Hr	Color Shift	$\leq \pm 0.008$
		Luminance Shift	$\leq \pm 10\%$
		Edge-Ingress	$\leq$ 1mm

*Range of parameter variation after the test is performed.
**Relative humidity.

TABLE VII
LUMINANCE VS UNIFORMITY CALCULATION OF THE QD-LED DEVICE FOR THE QDF LAYER USED IN THIS WORK

QDF	I_F(mA)	Luminance(cd/m^2)	Uniformity (%)
Luminance vs Uniformity	25	17000	89.1
	50	35000	88.6
	75	50500	87.5
	100	69000	89.1

I_F=140 mA from datasheet) as extracted from Fig. 11 from the luminous efficacy indicator. Thus, it is possible to state that the optimal driven current in our application is around 80 mA. Therefore, depending on the lighting application pursued, a specific blue LED should be careful chosen to comply with the automotive lighting values required.

Besides, the current efficiency indicator increases at low current injection levels and stays flat from 50 mA to around 80 mA. After that point, the efficiency is slightly reduced until 100 mA. Thus, as said previously, it is really important to select the correct blue LED source for the specific lighting application targeted.

Finally, the luminance given by the QDF was measured. This figure of merit is especially important in the automotive field, particularly in rearlamp applications for taillights [8], [24] since the homogeneous quality of the illuminating surface can be analyzed by calculating the uniformity (%) parameter written as

$$U = 1 - \frac{(L_{max} - L_{min})}{(L_{max} + L_{min})} \tag{3}$$

Where L_{max} and L_{min} are the maximum and minimum values of luminance in the specific lighting area measured.

Likewise, the luminance analysis has been performed by taking a 750 point-line going through 6 segments of the QD-LED device to finally obtain the uniformity U of the QDF layer for different currents applied to the blue LED source as shown in Table VII.

As observed, both the luminance values and the uniformity achieved by the QD-LED device are quite high, obtaining values between 80% and 90% for the different currents applied.

Fig. 13. Digital QD-LED device designed in this work with dynamic lighting scenario example (hazard warning mode). Car-to-X communication in rearlamps [7], [8].

C. PMMA Red Filter

Now this work will be focused on the taillighting function to compare the performance with the already validated automotive digital OLED technology. To do so, and after analyzing the QDF layer proposed, it is necessary to try to convert the bluish white color into red one. Thus, a red automotive filter made out of PMMA is added as the last layer of the QD-LED device. The PMMA is a transparent thermoplastic often used in the lenses of exterior lights of automobiles due to the fact that it is a strong, tough, and lightweight material, which is an economical alternative to other materials like the polycarbonate (PC) [25]. Thereby, a standard red-colored PMMA material with a thickness of 2.5 mm was used as red filter. Thanks to the electronics designed each segment can be activated individually, creating the digital QD-LED desired to transmit information to other vehicles and road users. That customized QD-LED feature, which is essential in the car-to-X communication for rearlighting [7], [8], is shown in Fig. 13.

Following the same procedure as the one done for the QDF layer, the output optical spectrum and chromaticity diagram were obtained using as input data, the output values of the QDF measured previously.

Therefore, a chromaticity analysis on the output optical spectrum was carried out in first place. Thus, using the spectrum obtained from the QDF and depicted in Fig. 8 as input, it is possible to obtain the final output spectral curves drawn in Fig. 14.

As it can be extracted from the red curve, two peaks are obtained due to the PMMA filter characteristics. The first one is centered on the input blue peak (465 nm) from the original blue LED source and the second one is positioned at the emission peak (624 nm) from the red quantum dot. It is worth saying that this red peak is also attenuated in an 8.3% due to filter response. Although the main objective of the red color filtering has been achieved, it is possible to analyze in Fig. 15 that the red output color ($x = 0.654$, $y = 0.297$) obtained is out of the automotive homologation area for the red color. This is due to PMMA filter response, which allows us to pass some blue light from the original source at 465 nm.

On the other hand, the luminous intensity was measured after the red color filter, where a lineal trend is predicted as shown in Fig. 16.

Therefore, following Table II, which defines the minimum and maximum luminous intensity values ([4, 17] cd for TAIL

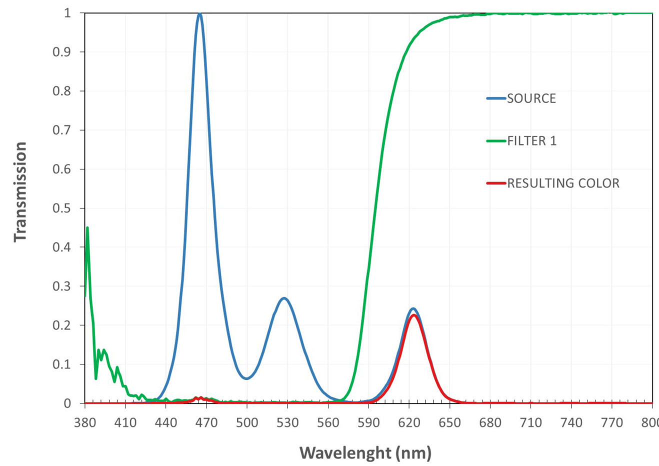

Fig. 14. Normalized spectral curves before PMMA filter (SOURCE) and after it (RESULTING COLOR). The green curve (FILTER1) is the PMMA transfer function for the material used.

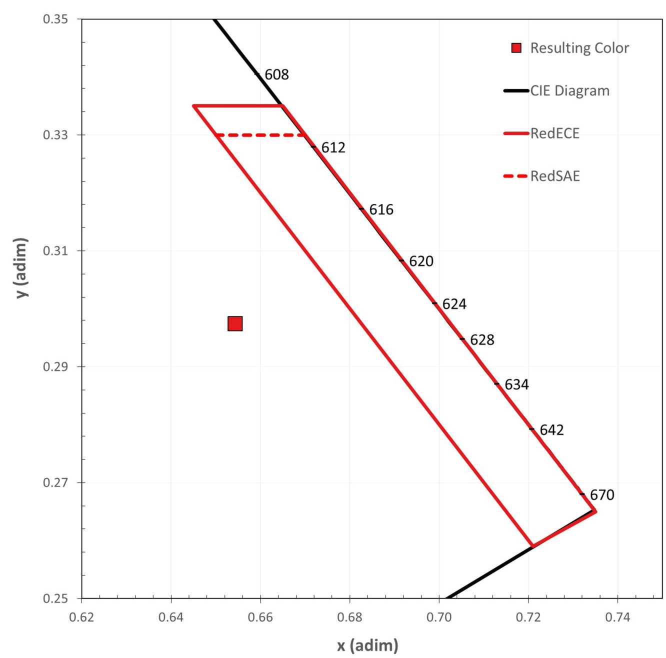

Fig. 15. CIE diagram centered on the legal automotive regulation area (red line polygon) for ECE and Society of Automotive Engineers (SAE) norms. Red square: resulting output color ($x=0.654$, $y=0.297$) after PMMA filter.

lighting function), it is possible to anticipate an optimal current range of the LED blue source in accordance to the fitting curve from Fig. 16. In this specific QD-LED system a range of current of [32, 95] mA for each segment would be necessary to comply with an automotive taillighting function.

Eventually, the luminance and the uniformity of this PMMA layer can be assessed. Thus, following the same strategy used for the QDF layer, those values were assessed. Moreover, in order to extract some conclusions, those measurements were compared with an OLED device. To do so, the results of the work made by Kruppa *et al.* [7], [8] were used as reference for the OLED values shown in Fig. 17.

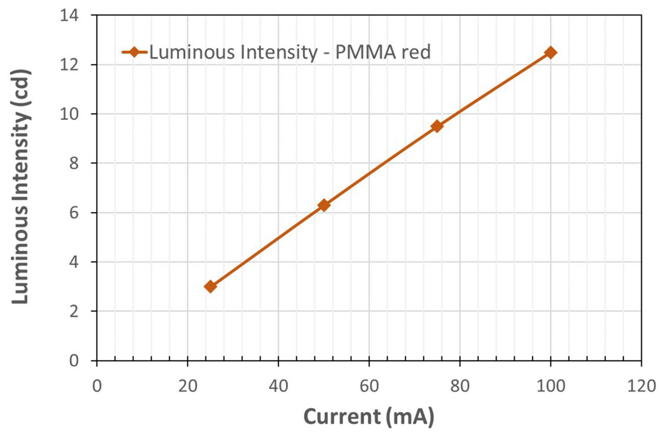

Fig. 16. Luminous intensity vs Current after the red PMMA filter.

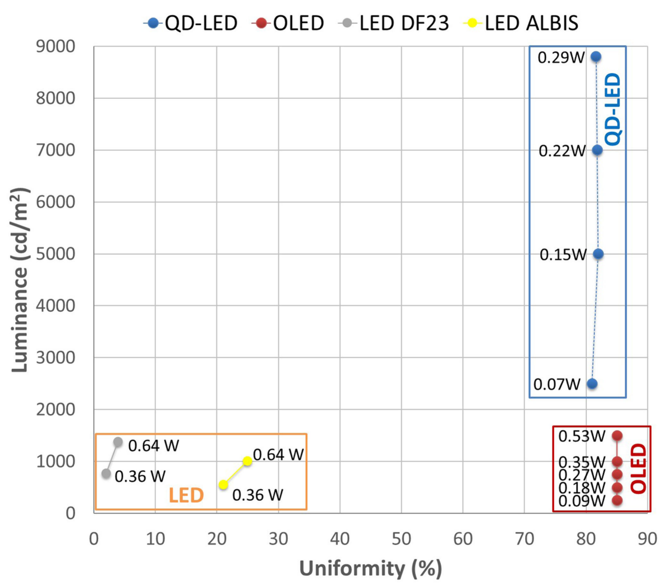

Fig. 17. QD-LED (this work), OLED and LED comparison of luminance vs uniformity values. OLED and LED values are extracted from Kruppa *et al.* [7], [8]. DF23 and ALBIS materials were used as optical diffussers of 1 mm of thickness. Typical $V_F = 2.9$ V from Table III is used in all cases as approximation to calculate the power in the blue source.

As it can be extracted from Fig. 17, uniformity values are higher for the OLED device than for the photoluminescence QD-LED one. However the uniformity values obtained for the QD-LED device (>80%) offer a promising approach to obtain uniform lighting surfaces for automotive lighting applications.

On the other hand, the values of luminance achievable from the QD-LED device are higher compared to the OLED device. This is due to the physical phenomenon used for the QD-LED, i.e. photoluminescence, where the quantum dot film acts as active conversion wavelength layer and not a mere dispersive layer. Thus, if QDF efficiency is improved and specifically designed for automotive applications, those values could be even higher.

Moreover, it is worth noting that OLED and QD-LED emissive areas under comparison are not the same [7], [8]. This is due to the specific mechanical constraints of the two automotive designs developed. Thus, the power shown in Fig. 17 for each value of luminance are not utterly comparable. It means that probably more than one blue LED source would be necessary to achieve the OLED areas considered by Kruppa *et al.* by keeping the same values of QD-LED uniformity. Therefore, a more accurate study, on both OLED and QD-LED devices should be carried out to extract a real power consumption comparison.

IV. Conclusion

Some general conclusions from this dynamic photoluminescent QD-LED device demonstrator may be set. As it was described, the main objective was to evaluate the suitability of QD-LEDs devices in the automotive industry, for which the electrical and optical parameters have been obtained to characterize the several QD-LED layers i.e. blue LED source, the QDF and the final device output when passing through a red filter.

Therefore, the blue LED source was measured and compared with the datasheet, establishing a good correlation between the theoretical and experimental data. Likewise, once the optical spectrum and the chromaticity points were totally defined for the blue source, the QDF output was measured, using the latter blue source as input excitation. Those measurements were quite interesting since it was possible to observe how the spectral plot changed and two new wavelength peaks appear. Those spectral contributions were due to the red and green quantum dots incorporated in the QDF. In the same way, the chromaticity coordinates moved to the white color. Nevertheless, since the QDF was not specifically designed, the blue contribution of the main source is very high and white coordinates are out of the automotive white color homologation. At this point, two possible actions should be taken into account if white color is pursued in future applications. Firstly, increasing the red and green spectral contribution by optimizing the density and QY of quantum dots in the QDF, and secondly, by adding some specific blue anti-transmission film to compensate the contribution of that color. Since the system efficiency as a whole could be affected by these actions, it is worth noting here that a compromise between both potential proposals has to be reached in order to obtain an optimal overall performance of the lighting device.

On the other hand, several figures of merit were extracted. Particularly, the luminous intensity was measured, reaching values comparable with different automotive lighting functions. Thus, without taking into account the color points and just the luminous intensity values, lighting functions like STOP, TAIL, TURN INDICATOR or even REVERSE would fit the performance given by the QDF for our fabricated QD-LED device. This is an interesting point, since by choosing the correct power blue LED source almost all automotive lighting functions could be implemented following this QDF strategy.

Moreover, performance indicators like luminous efficacy and current efficiency were calculated from the measurements. Those QDF indicators values could be higher in reality due to the light leakage in the QD-LED device built up process (the QD-LED is a proof of concept mockup) and to the instrumentation used. Likewise, both the quantum dots materials and the synthetization process should be revisited in order to increase the global QD-LED efficiency.

Furthermore, the luminance of the QDF was analyzed obtaining good values in the range of [15000, 70000] cd/m^2 compared to the ones required in automotive (2000 cd/m2) applications. In addition, the values of luminance uniformity between 80% and 90% for the different currents applied are in good agreement with the values expected for automotive lighting systems.

Finally, a red PMMA filter was used to implement the TAIL lighting function. The objective of the filter was to remove the blue and green spectral components by keeping only the red one. However, the filter material characterized allowed some blue spectral contribution. Thus, the final color calculated and measured was slightly out of the automotive homologation region and it would be necessary to use a different filter with distinct features. Likewise, the luminous intensity was measured reaching the conclusion that a range of main blue LED current of [32, 95]mA for each segment would be necessary to comply with automotive taillighting values.

Likewise, the final red filter layer luminance was measured and compared with an OLED automotive application. In this case, both the values of luminance [2500, 8800]cd/m^2 and the uniformity (>80%) achieved are inside the values required for automotive lighting applications, using a low and efficient power consumption.

Eventually, if an automotive lighting function implemented by quantum dots is desired using photoluminescence phenomena, both the blue LED source and the QDF layer have to be specifically designed. Therefore, if a red lighting function like taillighting or STOP is pursued for example, red quantum dots have to be used and a compromise between the blue excitation and the conversion to the red color has to be achieved to avoid final blue contribution. In the same way, if white color is required, the spectral contributions of the different quantum dots and the blue source need to be compensated to obtain regulatory values for automotive lighting systems.

Finally, automotive environmental and electrical tests are the future step to take to consolidate and validate a final automotive product. Results on these tests are on their way.

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