State of the art of a LED module using a Chip on Board technology

Abdenacer AIT MANI, Manon ARCH, Marianne CONSONNI, Guillaume JEFFROY, Laurent MENDIZABAL, Jean-Charles CIGNA, Adrien GASSE, David HENRY, Philippe ALIBERT *

CEA, LETI, Minatec Campus, 17 Rue des Martyrs- 38054 Grenoble Cedex 9-France

* Best, Parc d'activités Les Terres d'Or, Route de St Philibert, 21220 Gevrey Chambertin-France

Phone: 33 4 38 78 40 13, Fax: 33 4 38 78 15 13, email:nacer.aitmani@cea.fr

Abstract

Solid state lighting using LEDs is already the present and future of light sources for general lighting. However, these products still need improvements to target all the promising features of solid state lighting: (long life time at high LED junction temperature, packaging reliability, stability of the white light over time etc…).

The packaging[1] is one of the more challenging issue to reach top level electrical, optical and thermal performances of the state of the art. We led in this study the manufacturing of a LED module based on 12 sources using the Chip On board (COB) assembly technology with the goal to optimize all the important parameters to manufacture a state of the art product.

A special care was taken to customize the printed circuit board (PCB) to optimise its electrical, thermal and optical performances.

All the manufacturing operations were carried out using industrial processes and tools: screen printing for solder deposition, pick and place of high brightness LED chips, tunnel reflow furnace under controlled atmosphere, flux residues cleaning, wire bonding, electrical testing before and after encapsulation with phosphors. This last step consists of the use of silicone polymer filled with phosphors to convert blue light into white light. Automatic dispensing was used to shape the dome over the LED chips in order to obtain 12 sources as close as possible in shape and performances (CCT, CRI and flux).

A complete electrical, thermal and optical characterization of the manufactured boards was made; the main specifications are summarized here below:

- An Insulated Metal Substrate (IMS) board using COB and SMD components, ESD (Electro Static Discharge) and EMC (Electromagnetic Compatibility) protections included.
- Luminous efficiency > 90lm/w at high working temperature (> 85°C) and high operating current (> 700 mA)
- Correlated Color Temperatures (CCT) : 2900 K/4000K
- Thermal resistance lower than commercial LED components (typically less than 5 °C/W).
- A chromatic coordinate dispersion equal or less than 3MA (Macadam steps)

The thermal characterization was carried out, using a transient thermal analysis (T3STER© apparatus), the electrical one using a dedicated probe station and the optical characteristics have been obtained using an integrating sphere and a photo goniometer.

Finally, ESD protection measurements were carried out using the HBM (Human Body Model) until 8 KV (Standard IEC 61000-4-2) in addition to EMC testing.

Key words: LED (Light Emitting Diode), COB (Chip On Board), Rth (Thermal Resistance), ESD (Electro Static Discharges), CCT (Correlated Color Temperature), CRI (Color Rendering Index).

I. Introduction

Solid State Lighting with LEDs is expected to be the main lighting technology in a near future; this is a continuous growing market that nibbles every day the market share of incandescent, fluocompact or fluorescent lamps [2]

This is not only because of a temporary fashion, but the solid state light sources bring really a technological breakthrough leading to less energy consumption worldwide (higher yield than the competing sources), life time increased by a factor 10 or more. In addition, it enables flexibility in dimming modes, light color adjustment. A whole new era is also starting in the light decoration thanks to this technology.
But as always in a new technological field, there is another side that must be seriously considered to take the whole benefit from this new technology. The die emitting surface is generally as small as some tenths to a few mm², so that at the luminaire level can be considered as a punctual source with high power density. The new challenges are:

- How to effectively dissipate the generated heat?
- How to extract the light with maximum efficiency?
- How to convert the emitted wavelength to a given white light correlated color temperature?
- How to manufacture cost competitive luminaires in order to open a widespread adoption?

In our work, as we used commercial die LEDs from well-known manufacturers, we have focused our study on the first 3 items with the goal to manufacture a product industrially acceptable for general lighting. We have manufactured a module with a COB technology and we made a comparison of performances with a module using top level components as a benchmark. The direct mounting of the die on the substrate seems to be the best option to optimize the thermal resistance with a reliable solder joint and to give enough flexibility to target any CCT with the right phosphors mixing depending on the need of the final dedicated application.

II. Definition of specifications.

In order to manufacture the targeted product, a work was carried out to write the specifications based on the application. The main technological parameters are summarized in fig 1 while the optical ones are summarized in the table 2.
The substrate for LEDs is critical because it impacts electrical, thermal and optical performances of the luminaire; a special care was taken in order to design this substrate with the best compromise

Demonstrator size	Diameter 100 mm
Number of light sources	12
MCPCB stacking	Aluminum based
Conductive layers	Copper 35 µm
Insulation layer	100 µm dielectric
Solder mask layers	Standard
Copper layer finishing	Ni-Au
Particular specification	White Solder mask in the die area , black solder mask outside the LED area
ESD protections	Close to the LED die

Fig 1: General PCB specifications

The (Ni-Au) finishing is necessary in order to conform to the reliability of the gold wires used for LED connections (Ball bonding).The second table below summarize the main optical specifications.

Demonstrator size	Diameter 100 mm
Sources size	Chips LED 1x1 mm²
Flux/lm/W	1080
CCT	2900 K / 4000 K
Chromatic coordinates tolerance (Macadam)	3MA
Luminous efficiency	90 lm/W
CRI	> 80
Encapsulation	Silicone filled with YAG:CE-Nitrides phosphors

Fig 2: Optical specifications

III: Manufacturing of the COB module

After an optical inspection of the PCBs and the validation of a good electrical isolation between the substrate and the copper layout on top, the following process was applied with all operations performed in a clean room environment:

- Solder paste deposition
- Pick and place of the SMDs and LEDs
- Solder reflow
- PCBs cleaning
- Wire bonding
- Encapsulation

The detail of these steps is given below:

III-1 Solder paste deposition

Based on the standard SAC (SnAgCu) metallurgy, the solder paste was dispensed using the screen printing technology with automatic equipment in order to ensure a reproducible quantity of paste for all the 12 dies.
A screen made of stainless steel stencil was used for this operation, stencil thicknesses between 50 -80

µm were tried with the goal to reach the best solder joint after the reflow process.
The picture figure 3 show a typical solder deposition used for the LED module manufacturing:

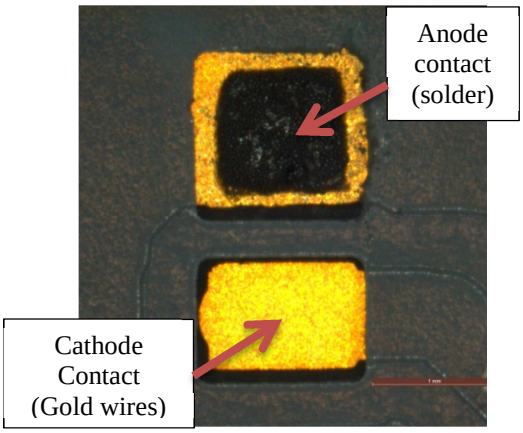


Fig 3: Typical solder deposition

III-2: Pick and place of SMDs and LEDs

The pick and place operation was carried out on an automatic industrial equipment. As the SMDs (Placed in a chip carrier) and the LEDs chips (on adhesive tape) were not on the same supplier packaging, we had to adapt the tools in order to guarantee the following parameters:

- The right pressure while ejecting from the tape and placing the die LEDs (which are more brittle than the SMDs).
- ESD control for safer picking and placement of the LEDs.
- Accurate position after placement on the solder paste in order to avoid unexpected behavior inside the soldering furnace.

Once the program and the parameters of the equipment carefully set, the SMDs and LEDs chips deposition on the board was done in the same conditions for all the manufactured boards.

III-3: Solder reflow

In the industrial field, there are many options to achieve the soldering process, hot plates, static furnaces, tunnel furnaces, wave soldering, vapor phase soldering …..
To conform to a potential high volume manufacturing need, the solution chosen was the use of a 5 zones tunnel furnace, the soldering being done under a neutral atmosphere (N2).

The optimized soldering profile used for our study is shown figure 4 below. The profile used is characterized mostly by a peak temperature of 255 °C and a total cycle time of 7 minutes. The average slope seen by the boards before the end of soldering peak is about 0, 6 °C/s.

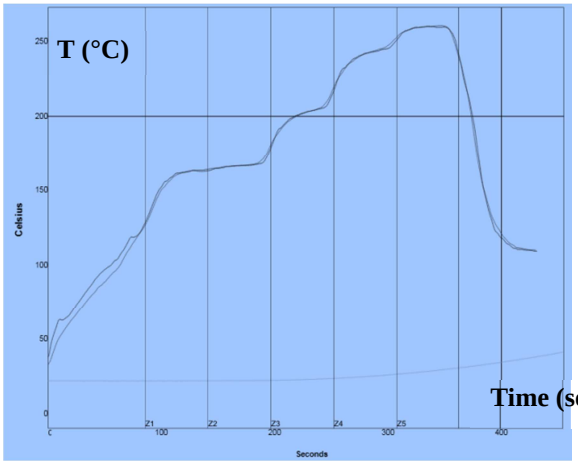


Fig 4: Soldering profile

To check that our soldering process is at the state of the art, shear test and cross sections were done, the results are given in the paragraph IV below.

III-4: PCBs cleaning.

The solder paste used in our study is a so called no clean one, because of the small amount of flux inside the blend. In most cases in the industrial electronic field, the cleaning step is just an option and the equipped boards can work for many years without the cleaning operations, the residues being chemically neutral in a dry state.
In our case, this step is mandatory because the soldering operation is not the last one as we still have to perform the wire bonding operation and the polymer encapsulation.
The flux residues even in small amount are not compatible with the gold ball bonding for LED connection, and also not compatible with polymer encapsulation (adhesion issues), in both cases the surface contamination created by the flux residues degrade the quality of adhesion.
So to manufacture a reliable wire bonding and encapsulation, the cleaning step is a crucial operation.
This operation is carried out in 2 steps:

- Wet cleaning ultrasonically assisted to remove the major quantity of flux residues.
- Plasma O2 to finish removing the non visible residual layer surrounding the solder sites.

To confirm this, an EDX control was done targeting any traces of organic residues; the result is shown in the picture below (fig 5), only tin material is found on the same targeted point before and after the cleaning process.

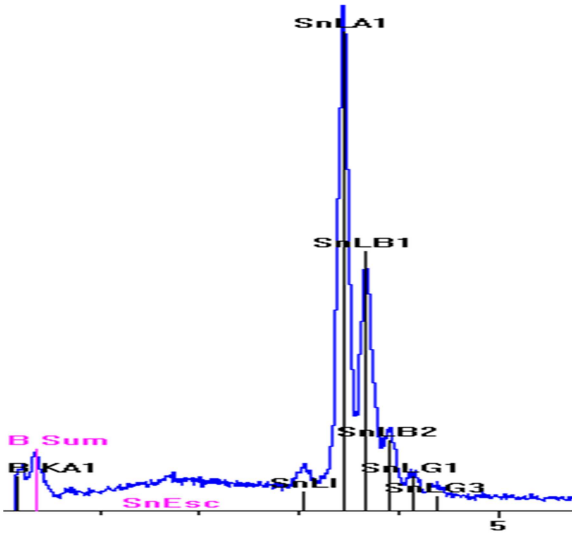


Fig 5: EDX control before Bonding and encapsulation

III-5: Wire Bonding

The manufacturing of our COB luminaire is based on Cree EZ1000 die having 2 gold pads for the cathode connections while the anode connection is on the whole back side surface. The rear connection is obtained through the SAC solder joint.
The wires for the top connection are 33 µm Gold.
As the layout of the luminaire PCB and the placement of the chips are not compatible with automatic wire bonding, this operation was done manually on a semi-automatic tool.
However, to check the initial reliability of the gold bonds, pull test measurement have been done as detailed in the characterization paragraph below.

III-6: LEDs encapsulation

As shown on figure 6 this operation was carried out in two steps:

- Deposition of the silicone polymer filled with a mixture of YAG:Ce and red nitride phosphors directly onto the chips (conversion layer from blue to white light).
- Silicone dome shaping for optimal light extraction

The preparation of the products to be dispensed on the dies was carried out using a planetary centrifugal mixer; it contributes to have the same optical mixture for all the 12 sources.
To master the volume deposited on the dies, we have used a volumetric dispenser with a targeted value of 10 mm^3.
Optical simulations and calculations help us to target a ration H/R (Height/Radius) close to 0, 8[3]

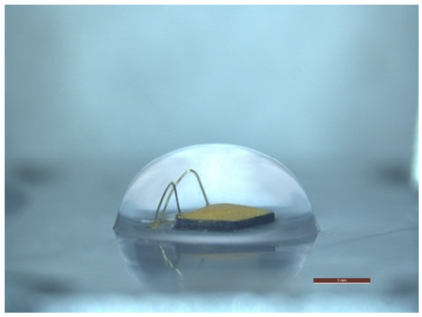


Fig6: Double step LED encapsulation

The figure below shows the module powered at 350 mA.

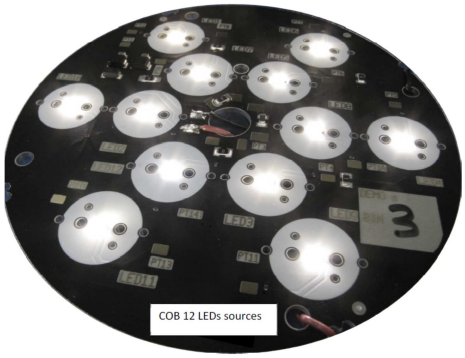


Fig 7: Chip On Board LED module

IV: Module characterizations

This work has concerned the electrical characterization of the LEDs by measuring for each source the I (V) behavior, the mechanical characterization in order to check that the shear test values of the solder joint and the pull test values of the wire bonding are at the level of known state of the art.
This work was completed by the thermal and optical behaviors of the light sources to check how far we are from the initial specifications and to compare our results to the same module in a standard package ready to solder (XP-E component from CREE in our study).

IV-1: Solder joint characterization.

In most cases, in the electronic industry and especially for the LEDs assembly, the solder joint is critical and its quality has a direct impact on the chip behavior and reliability of the luminaire.
To claim that the manufactured product is at the state of the art, we must precisely analyze the interface between the chip LED and the substrate after the soldering step.
The picture below (fig 8a and b) shows the cross section and analysis of sampled dies:

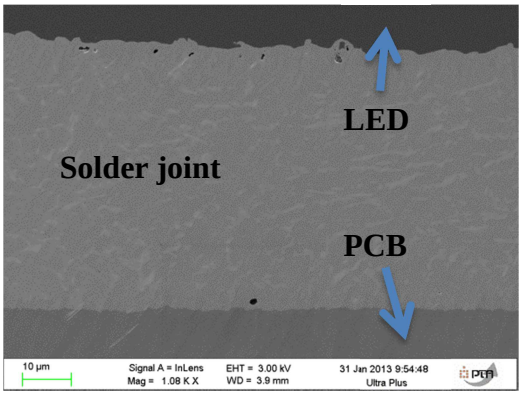


Fig 8a: SEM cross section at the solder interfaces

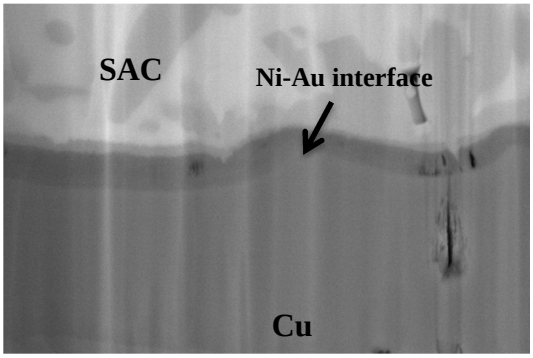


Fig8b: Zoom by FIB on the solder joint

We can see as typically in the SAC solder joints [4] some small bubbles left inside the solder joint. Of course, a specific work on the soldering process like the use of another atmosphere than Nitrogen (Formic acid, forming gas, vacuum…) could give a better result with less voids but in this case we had to stay as close as possible to high volume capacity.
What is important to keep in mind here is that at both interfaces, the wettability is excellent making a very reliable interface for thermal and electrical conductions.

IV-2: Shear test characterization.

This parameter is also of concern in order to check that the mechanical strength is also at the state of the art as usually found in the microelectronic packaging industry.
Carried out with a Dage tool, the results of the 12 die shear strength are summarized in the table figure 9. Compared to the usual values based on the mil-STD-883G criteria, all the results are higher than the specified value (Die shear >1, 3 Kg), showing that the soldering process and the die attach used are conform to the state of the art with a high reliability level.

Die Number	Shear test value (Kg)	Average value (Kg)
1	3.6479	**3.7771**
2	3.9249	
3	3.2193	
4	3.7448	
5	3.2513	
6	3.7251	
7	5.5048	
8	3.3472	
9	3.1585	
10	3.1531	
11	4.8640	
12	3.7849	

Fig 9: Shear test values

IV-3: Wire bonding characterization.

Few boards were manufactured in order to do the trials for gold ball bonding qualification. The conditions are the same as the delivered board of the project.
As for the shear test qualification, the tool used is the Dage 4000+, this time in the pull test mode, the typical wire bonds before the tests are shown in the picture figure 10 below.

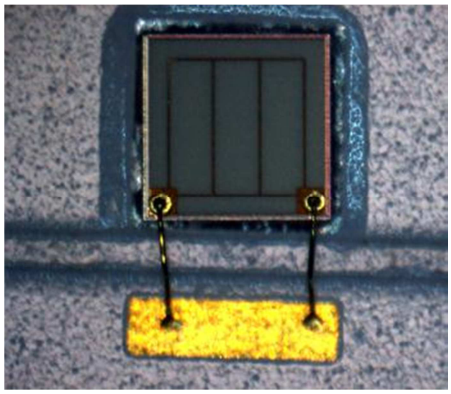


Fig 10: Gold wire bonding on EZ1000 Led

More than 50 pull tests were done to check the reliability of the process. A minimum measured value of 9 gr has been registered with the breaking of the gold wire confirming the compatibility with the encapsulation process.

IV-4: Silicone Dome characterization.

Encapsulation of the LED is a very critical operation, because if not done carefully, some emitted light can be lost by reflection, poor conversion efficiency (phosphors losses), poor

refractive index matching between the LED surface and the polymer and finally the presence of air bubbles inside the dome.
Additionally to the light extraction issue, the dome acts as a protection for the chip and must adhere simultaneously to the die and to the substrate. The continuous thermal stress due to the LED operation must not degrade the adhesion and the optical values. The manufactured domes were also tested mechanically with the shear test tool.
This operation, not straightforward on a very soft surface gave very scattered results. This issue was overcome using a suitable adhesion promoter.

IV-5: Electrical characterization.

The I(V) measurements for each die of the luminaire were completed by ESD testing to check the robustness of the equipped boards (COB and XP-E component) when unexpected electrostatic hazards happen.
For each chip LED of the board, the ESD protection is provided by a TVS SMD from On Semiconductor. It is soldered close to the die and completed by a general protection with another TVS chip at the input of the Board supply.

The system ESD robustness level has been checked by carrying out qualification tests on representative boards, following the IEC 61000-4-2 requirement. This qualification test consists in the application, by contact, of calibrated waveform voltage pulses (0.7 to 1 ns for rise time between 10% to 90% of the pulse – 3.5A/kV) on the IO pads of the system. The pulses voltage increase at each test level (1kV, 2kV… until 8kV), and is applied 10 times by step.

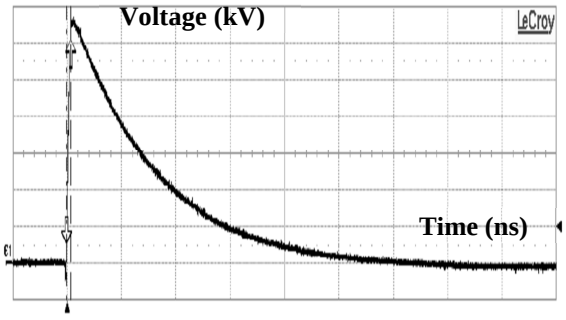


Figure 11: ESD Waveform (ESD pulse in kV function of time in ns)

This method has been applied on two kinds of board: the first based on commercial XP-E LEDs, and the second based on COB ones with added TVS. Four boards of each kind have been tested. A comparison of the first failures apparition steps leads to a result of 4kV for commercial LEDs based board and 6kV for COB ones.

The failure mode, observed on COB as well as on the XP-E boards, was a linear resistive behavior of the LED. The I(V) measurements, carried out at each voltage step, show a gradual degradation characterized by the increase of the leakage current, until reaching the series resistance level (figure 12). An hypothesis for the explanation of this behavior, is the creation of a leakage path through the active layer of the LED, shunting the MQW layer, and leaving only access and internal series resistance.

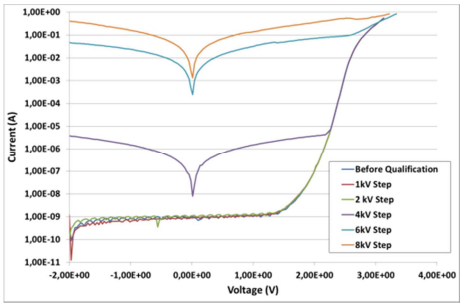
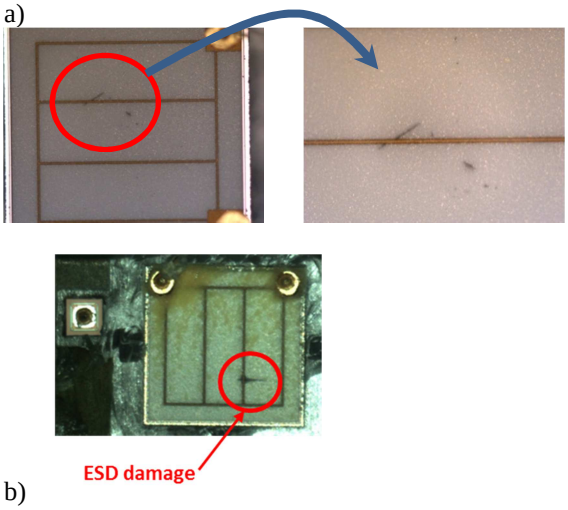


Figure 12: Representative example of I(V) characteristic monitoring during ESD Level qualification

This hypothesis is confirmed by optical observations. In figure 13, impacts can be observed on the surface of the die. This "scare" is characteristic of ESD defects. Figure 14 presents the LED powered around 3V. A non-emissive area can be observed around the ESD impact that is not observed during assembly process control measurements.

a)



b)

Figure 13: Observation of ESD impact on LED surface in a) COB configuration (defect level: 6kV) and b) XP-E component (defect level: 4kV)

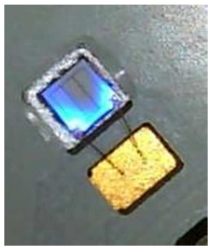


Figure 14: Observation of non-emissive area of defected powered LED

So using SMD TVS components, we are able to manufacture LED COB modules having a higher robustness against ElectroStatic Discharge compared to standard XP-E component modules.

IV-6: Thermal characterization.

Since the expected thermal resistance should be lower for the COB module than the CREE XPE equivalent module, we use a dedicated tool (T3ster©) to check it [5]; the graph figure 15 shows the behavior of the two modules:

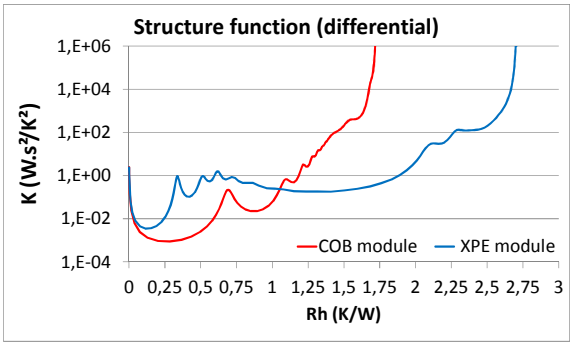


Fig 15: Thermal behavior comparison of a COB and component module

The extracted thermal resistances from the graph show that the Rth value for the COB module is 1.73 K/W while it is 2.7 K/W for the XPE module.
This thermal resistance difference leads to a junction temperature of 116 °C for the COB versus 134°C for the XPE module which is very critical for both efficiency and reliability.
The measurements were carried out using the same current in the range from 350 to 700 mA.
It is clear when looking at the graph that the COB module has better dissipation capabilities than the component module.

IV-7: Optical characterization.

Optical efficiency is the main output parameter because the aim of the chip LED is to bring the light to the user with a minimum of losses (heating of the junction, bad encapsulation leading to poor light extraction…).The measurements were carried out in an integrating sphere for the spectral curve of the light source and with a goniometer to have the angular intensity, the results are shown figures 16a and b below. It is interesting to note here that the flexibility of the COB configuration allow us to target warm white and neutral white on the same module.

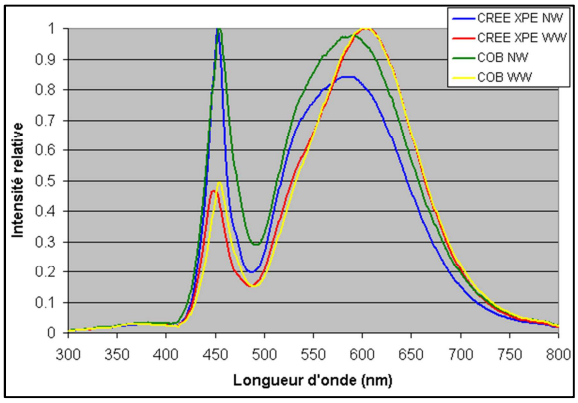


Fig 16a: Spectral curve of the COB and XP-E source

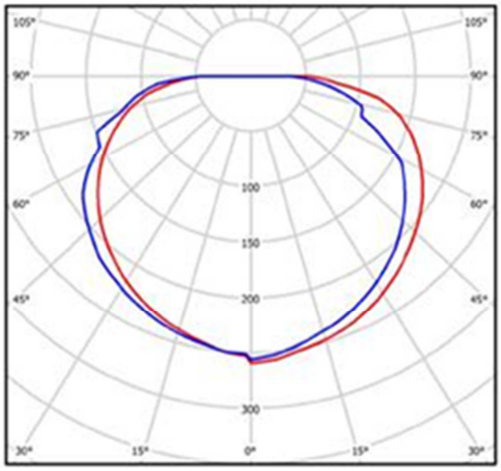


Fig 16b: Distribution diagram of the COB source

The beam angle (FWHM) is almost the same as the XP-E module which has a lambertian pattern (120°) but the distribution is slightly enlarged at angles above 60°.

Concerning the efficiency, it is 62 lm/W at 700 mA driving current at thermal equilibrium (75 at room temperature) compared to 58 lm/W (70 at room temperature) for the XP-E module.
Note that in both cases, the efficiency is lower than expected. It is due mostly to the fact that the efficiency is measured at 700 mA to evaluate the worst case. Driving the LEDs at 350 mA increase the efficiency of up to 35 % in both cases and largely overcomes the efficiency targets.
In both cases, the CRI is of 80.

V: Conclusion

The work that we carried out in this study has clearly shown that the COB technology can answer to the expectations of lighting in terms of design flexibility [6], white light quality and optical performances. Confirmed by the manufacturing of more than 10 demonstrators, if all the technological steps are carried out using the right tools and processes, the final product is robust mechanically and electrically justifying its use in an industrial environment more demanding in terms of electrical protections .This robustness facilitates of course its use in the domestic sector.

Acknowledgment

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