

Analysis of the spectral degradation of LEDs' emissions under temperature stress conditions

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Abstract – This paper presents the experimental results of an accelerated-life-test carried out on colored LEDs under temperature stress conditions. The main purpose of the work has been to investigate over the dependence of their reliability vs. their color. A deep analysis of the time variation of spectral components (RGB) under thermal stress has shown that the spectral components for each colored LED change in a different way over time. The main conclusion of this work is that the reliability of LEDs is strongly affected by the procedure and elements used for coloring the LED yielding to have different reliabilities for different colors.

I. INTRODUCTION

Light emitting diodes (LEDs) offer a number of advantages compared to conventional light sources such as: reduction of the dissipated power, higher spectral purity, longer life, better response time, lower supply voltage, lower cost, all facilities for continuous improvement. Some of the major applications are road safety systems (traffic lights, warning systems, etc.), lighting for machine vision systems, in automotive with the backlight LCD display, etc. However, there are some disadvantages: the LEDs do not fail instantly, but have a slow degradation in brightness and color, phenomenon called "spectral degradation". The estimated duration of the current LED devices is of the order of 50,000 hours for less demanding lighting applications. Thus, much shorter life spans are to be expected for critical and demanding applications.

The spectral degradation is particularly critical for applications such as machine vision systems, whose performance is significantly affected by every change of brightness. Another problem is the variability of degradation within the same batch of LEDs. Additionally, the optical properties of a LED, such as intensity, color and spectrum of the emitted light can vary due to the change of the manufacturing process. These problems require frequent calibration and/or sophisticated image correction techniques. Several techniques - such as inspection systems with spectrograph, brightness measures - have been proposed to reduce this variability within the same

batches of the product. All these solutions, however, should come together with adequate models of LED behavior in terms not only of brightness, but also of chromaticity.

For all these reasons there is a strong interest to deeply investigate in general over the performance and especially over the degradation of both the brightness and the chromaticity of the light emitted by LEDs under different stress conditions. In [1], a both theoretical and experimental analysis of the degradation of the light spectrum of different LEDs has been performed by considering the effect of the forward current whereas in [2], the authors of this paper have analyzed the reliability of LEDs vs. the applied forward current. It has been experimentally shown, as well as by means of an innovative reliability model, the strong dependence of the LED reliability on the value of applied current.

In the present paper, the reliability analysis focuses on the effect of temperature stress. More in particular, a sounder and deeper investigation is performed on the effects of temperature on the different main spectral components of the light emitted by LEDs.

Hereafter, a brief introduction describes the process of color generation in LEDs and the mechanism of human perception. Then, the procedures used for performing the accelerated life tests under temperature stress conditions are described along with the whole test set up. Finally, the measurement results are reported in terms of time-to-failure of LEDs of different colors at different temperatures

II. COLOR IN LEDS AND HUMAN PERCEPTION

The color is a property that allows distinguishing between different types of lights. It is fully defined in terms of human perception and can be characterized in terms of:

- Brightness, namely color intensity
- Tone, namely dominant color
- Saturation, namely color purity, or the amount of white light mixed with the dominant color.

The tone and saturation jointly form the color chromaticity. The physical property of light that defines the color is its spectrum (power spectral distribution), which shows the intensity distribution of the light as a function of the wavelength. The shape of the spectrum determines the

chromaticity of the light, while its amplitude determines its brightness. The variation vs. some of these properties in the light emitted by LEDs are considered in this paper.

II.A The human eye and the color space

The human eye has three types of cone cells, each detecting the light with spectral sensitivity peaks spread over more or less wide wavelength ranges, namely:

- short (S), over the range 420-440 nm;
- medium (M), over the range 530-540 nm;
- large (L), over the range 560-580 nm.

These cone cells are the basis of the perception of color under medium and high light conditions. Consequently, the three parameters can describe any sensation of color. These three values form a specific color tristimulus and can be represented by using a three-dimensional space, called LMS color space. However, this representation is not so useful for practical application and hence several other kind of space colors have been proposed since the first CIE 1931 [3] was developed in the 1930s. The most common ones, and that have been used in this work, are the RGB and HSL color space.

The RGB color space is based on an additive model of three basic components (Red, Green, Blue), each of them can take an arbitrary intensity, from fully off to fully on. When all the components are fully off (zero intensity) the obtained color is the darkest one (black) whereas when all the components are fully on (maximum intensity) the resulting color is white. The “kind” of “black” or “white” depends on how are defined the primary component.

The HSL color space relies on cylindrical representation of the color by using Hue, Saturation and Lightness as coordinate. Hue is the angle around the central axis, saturation is the distance from the axis and lightness is distance along that axis. Analytical expression allows changing from the RGB to HSL representation and viceversa.

III. LIFE TESTS AND MEASUREMENT SET-UP

Based on the above theory, an experimental campaign of



Fig. 2 Junction box of the LEDs and optic fibers inside the thermostatic chamber

accelerated life tests (ALTs) on colored LEDs is in progress at the Laboratory of Electrical Measurements of the University of Bologna. These ALTs are carried out on samples consisting of 15 LEDs (5 red, 5 green, 5 blue). All the LEDs feature a rated forward current of 20 mA and have T-1 package. Their operating temperature is 60°C. In particular, the red LEDs have a dominant wavelength of 625 nm, which is 575 nm for the green ones and 466 nm for the blue ones. To ensure that the effect of the forward current on their aging can be considered negligible, all the LEDs are fed with a constant current of 15 mA. This way, the only aging factor is the temperature that is applied by keeping them inside a thermostatic chamber. Such chamber allows to control the temperature between -40°C and +180°C with an accuracy of $\pm 0.3^\circ\text{C}$ and a uniformity of $\pm 1.5^\circ\text{C}$. To date, three tests at 160°C 150°C and 140°C have been completed.

Fig. 1 shows a schematic representation of the measurement set-up. The devices are monitored through a camera and all information on the LEDs status are obtained

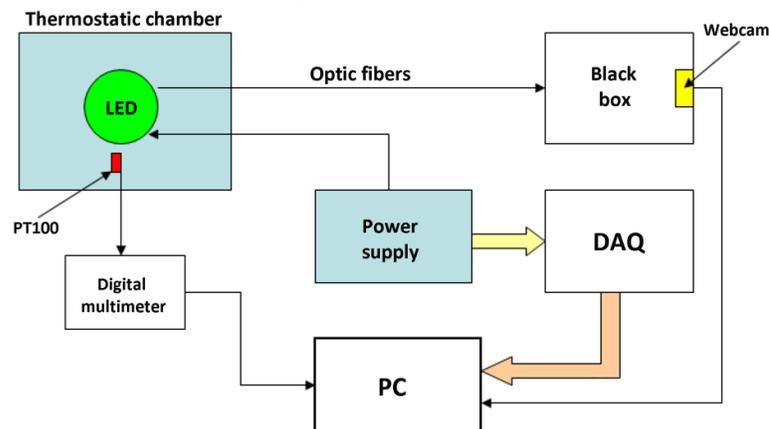


Fig. 1. Schematic block diagram of the measurement setup

by processing the acquired images. To prevent the camera from being subjected to the same thermal stress of the LEDs, it is positioned outside of the thermostatic chamber and an optical fibers (suitable for high temperature operating range) is used for each LED to deliver the emitted light. This way, the camera can capture the images of all the LEDs in a suitable temperature stress-free environment. Fig. 3 shows the junction box between the LEDs and the optic fibers inside the thermostatic chamber. Fiber optics end inside a black box where they are fixed to a wall with circular shape. The camera is located at a distance of 20 cm from the center of the circle. The adopted solution of fiber optics and camera placements has been verified to be the most suitable one for allowing the camera to acquire the maximum luminous flux from all the LEDs at the same time and by minimizing the well known nasty effect of the optical vignetting (see Fig. 3).

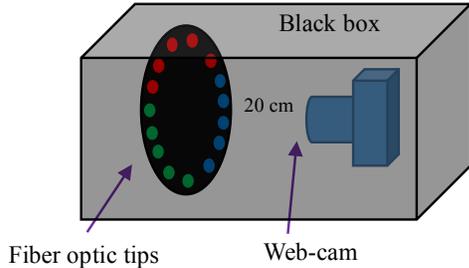


Fig. 3. Sketch of the black box realized

Also voltage drop and forward current are measured for each LED by means of 3 National Instrument PCI-6023E (DAQ) with 16 single-ended (or 8 differential) analog inputs, 12 bit resolution and 200 kSa/s sampling rate. Two DAQs are used for the acquisition, in differential mode, of the current samples, given that resistive shunts, placed between the power supply and each LED anode, are used. The third DAQ is used for acquiring, in single-ended mode, the samples of the 15 voltage drops.

Additionally, the temperature inside the thermostatic chamber is measured. To this purpose, a temperature-dependent resistor (PT100) connected to a digital multimeter, controlled via IEEE 488 protocol by the same PC used for all the other measurement, have been used.

As already mentioned, all optical parameters are obtained through the images taken by the camera (Logitech HD Pro webcam) whose main parameters, such as brightness, contrast, exposure and focus can be remotely set via Labview. All images, taken every 5 minutes, are sent to the PC via USB and stored for successive processing.

IV. TEST RESULTS

The main parameter considered for estimate the time to failure of a LED is its (residual) brightness. According to [4,5], the LED is assumed to fail as soon as its brightness

drops below 70% of its original value.

Every stored images shows the lights emitted by all the 15 fiber optic tips, each of them corresponding to the light emitted by one of the LED inside the thermostatic chamber. Firstly, the properly-developed software, whose front panel is shown in Fig. 4, processes every single picture by dividing it into 15 different sub-frames, one for each tip-light. Then, for each sub-frame, the RGB and HSL parameters are evaluated for every pixel belonging to the LED image.

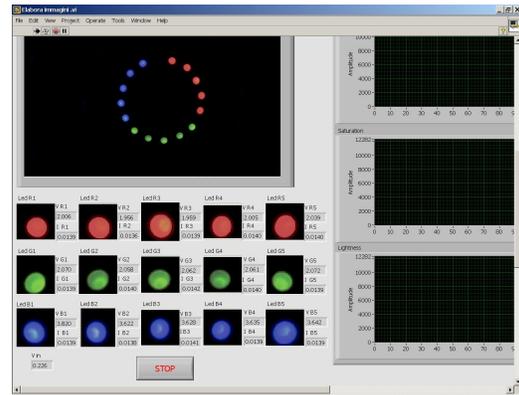


Fig. 4. Front panel of the realized software with the decomposition of the frame into 15 sub-frames

For each color component, the mean value is computed, thus obtaining $\bar{R}_{k,m}$, $\bar{G}_{k,m}$, $\bar{B}_{k,m}$, where k refers to the k -th image acquired at the time instant t_k and m to the m -th LED. After that, the residual brightness is evaluated, for the m -th LED at time t_k , in terms of overall residual brightness $RB_{k,m}$ as well as color-component residual brightness $RB_{i,k,m}$, where i can be R, G or B. As for $RB_{k,m}$, it is computed as follows:

$$RB_{k,m} = \sqrt{\bar{R}_{k,m}^2 + \bar{G}_{k,m}^2 + \bar{B}_{k,m}^2} \quad (1)$$

As for $RB_{i,k,m}$, it is equal to $\bar{R}_{k,m}$, $\bar{G}_{k,m}$, $\bar{B}_{k,m}$, depending on i .

On the basis of the above definitions, for each LED, four times-to-failure, $t_{f,R,m}$, $t_{f,G,m}$, $t_{f,B,m}$ and $t_{f,m}$, can be estimated. Finally, for each kind of LED, the mean-time-to-failure of each spectral component, namely $MTTF_R$, $MTTF_G$ and $MTTF_B$, and the overall mean-time-to failure, $MTTF$, can be computed.

Table 1 shows the values of $MTTF_R$, $MTTF_G$ and $MTTF_B$, as well as the overall $MTTF$, obtained for the red LEDs at 160°C, 150°C and 140°C. Table 2 and Table 3 report the same parameters for the green and blue LEDs, respectively.

Firstly, it can be observed that the blue LEDs are the ones having the lower $MTTF$ s in all the tests. In fact, their life is from 4 to 8 time shorter than that of the other LEDs, depending on the temperature and the kind of LED to

Table 1. Mean times to failure of the red LEDs

Temperature (°C)	MTTF _R (h)	MTTF _G (h)	MTTF _B (h)	MTTF (h)
160	187	64	113	130
150	321	206	258	281
140	644	100	230	591

Table 2. Mean times to failure of the green LEDs

Temperature (°C)	MTTF _R (h)	MTTF _G (h)	MTTF _B (h)	MTTF (h)
160	290	224	337	276
150	385	344	458	426
140	445	444	661	525

Table 3. Mean times to failure of the blue LEDs

Temperature (°C)	MTTF _R (h)	MTTF _G (h)	MTTF _B (h)	MTTF (h)
160	46	40	29	39
150	31	84	64	68
140	26	106	135	108

which is compared to.

The green LEDs, except when the temperature is 140°C, are the one showing the greatest values of MTTF. At 140°C, their MTTF value is substantially equal to that of the red LEDs.

The reasons of such behavior is still under investigation, however two main hypothesis can be done: (i) the forward voltage of the blue LEDs is much greater (3.9 V) than that of the green (2.4 V) and red (2 V) ones, thus leading to more power dissipation under nominal current conditions; (ii) the technology on which such LEDs relies on is less well-assessed than that of green and red LEDs, that are on the market since much longer time than blue LEDs: the criticalities involve the doping of the semiconductor material as well as the connections of the blue LED

The second observation deals with the variation of the MTTF versus the variation of the temperature. The simple calculation of the ratios between the MTTF at different temperatures highlights that red LEDs feature the highest increasing of their life when the temperature decreases. The behaviors of blue and green LEDs are rather similar one to each other.

The third consideration deals with the values of MTTF_R, MTTF_G and MTTF_B. The fact that, for the same

temperature, different values are gauged denotes that the ageing of the device has caused, in addition to a decreasing of its brightness, also a variation of its color.

This is confirmed by the pictures shown in Figs. 5a e 5b, which, by way of example, refer to a red LED tested at 140°C. In particular, each plot represents, for the different intensity (in a scale from 0 to 255) of the components R, G and B the number of pixels having such intensity. It is quite easy to verify that at the end of the test the light emitted by the LED is not only, as expected, less bright but also different in color. The same conclusion can be drawn, in a simplest way, from Figs. 6a and 6b which refer to the same LED in the same test. They show the average value of the intensity of the R, G and B component and hence, in other words, are a schematic representation of the spectrum of the light emitted the LEDs. The difference between the two situations is clear.

Similar considerations hold for the other two kind of LEDs.

V. CONCLUSIONS

An experimental setup has been developed to investigate on the ageing of LEDs of different colors when a thermal stress is applied.

Accelerated life tests have been performed at three different temperatures and the lights emitted by the LEDs under test have been monitored by means of a camera and processed to analyze the relevant R, G and B component.

The obtained results highlight the spectral degradation of the light emitted by the LEDs under test, in terms of both brightness and chromaticity.

In particular, it has been shown that the blue LEDs are the ones showing the lower MTTF and that the ageing of all the kind of tested LEDs is associated to a variation of their chromaticity.

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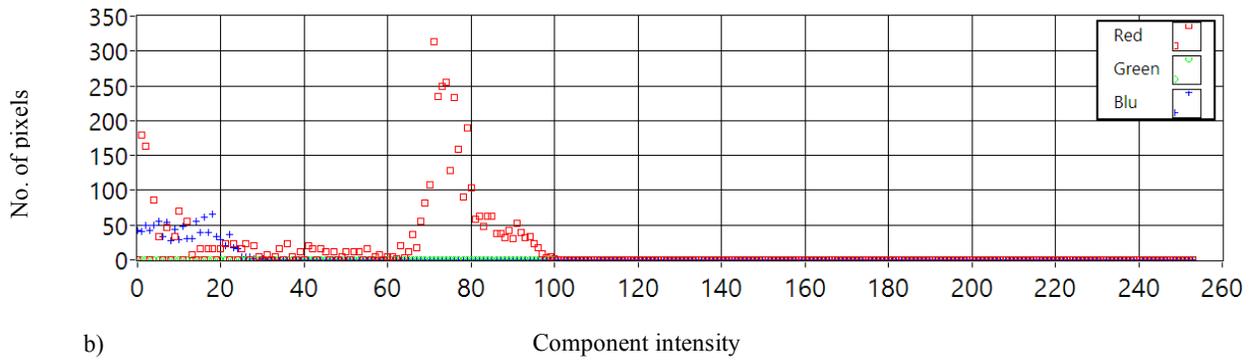
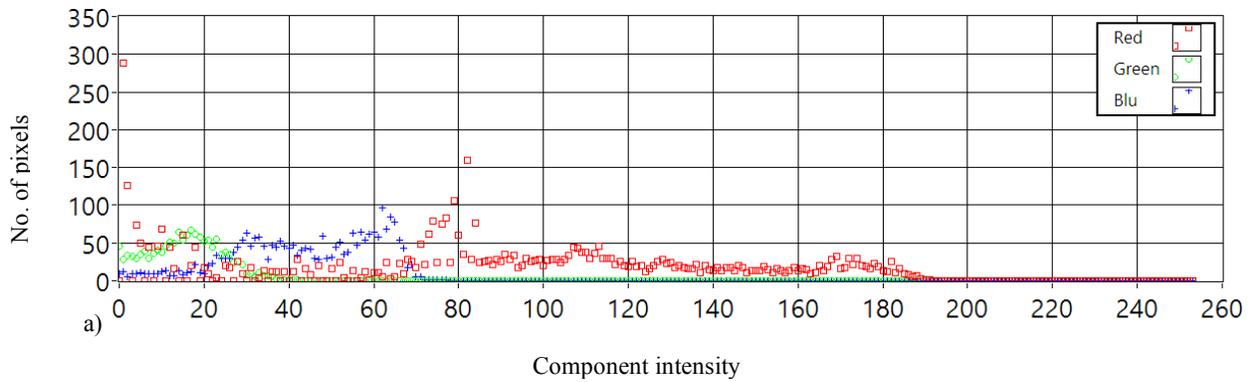


Fig. 5 Spectra of the red component of red LED at the beginning (a) and at the end (b) of the test when the temperature is 140°C

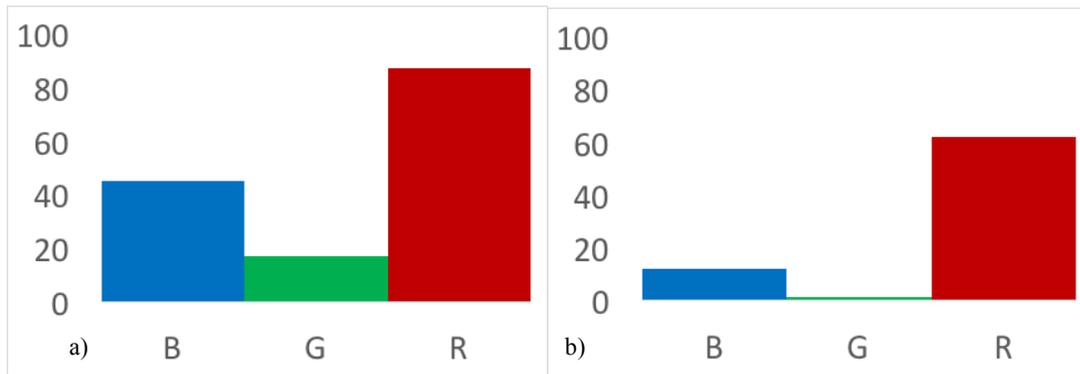


Fig. 6 Average intensity of the RGB components at the beginning (a) and at the end (b) of a test (red LED, 140°C)

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