PROJECT PERIODIC REPORT

Publishable Summary

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This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement **no 619912**

Project Final Progress Report
Publishable Summary

Project Acronym	**HI-LED**
Project title	**Human-centric Intelligent LED engines for the take up of SSL in Europe**
Website	www.hi-led.eu

Collaborative project

FP7-ICT-2013-11

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RE	Restricted to a group specified by the Consortium (including the European Commission Services)	
CO	Confidential, only for members of the Consortium (including the European Commission Services)	

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Spectrally tunable lighting offers a new paradigm associated with the possibility to mimic any light spectrum imaginable in the visible range. Spectral optimization gives rise to a full range of potential applications where specific spectral components are critical or play an important role while, at the same time, allows control over energy efficacy by adapting those components to regions where the particular application is more sensitive to.

HI-LED project aims at conducting research on spectrally tunable light engines with added intelligence, that are cost-competitive in the high-end market and energy-efficient, in connection to a broad and multidisciplinary team, deemed necessary to validate the results, final claims and impact in diverse applications. In addition, since conventional LED technology fails to provide efficient devices in certain wavelengths of interest, the project also focuses on OLED technology as a potential replacement.

Spectral reproduction/tailoring concept exploited in HI-LED is well suited for a wide variety of applications where an optimum balance between energy efficiency and light quality is an asset. Three are the case studies investigated in the project: horticulture, human-centric lighting and art-work visualization. Once the universal light engine, able to produce any visible spectrum in a controlled manner, is available, these studies have determined the contents of the spectrum needed to produce optimal results in each case.

The multidisciplinary nature of the project allows us to separate the results into the technological challenges affecting the design of the intelligent light sources themselves and the selected applications:

RESULTS FROM THE LED MODULES AND LUMINAIRES

1. LED modules with digital intelligence and spectral tunability

- Luminaire integration
    - Reduced dimensions
    - Compatible with OTS heatsinks (Zhaga books 2&5)
    - Integrated electronics
- Manufacturing
    - **>60% reduction** in number of components
    - Simple vertical assembly (designed for automation)
- Output flux >**3500 lm** for the same electrical power input (52W).
- Minimum efficacy of 67 lm/W (full power), with a roof of 125 lm/W (lime channels), and typical of 90lm/W. This is a major achievement in the project, since typically existing multichannel solutions are very inefficient (between 20 and 60 lm/W) for the same colour mixing quality.
- Reduced junction temperature (about 60ºC) for the same heat sink (longer life)
- Electronics
    - No flicker (20kHz modulation) and noiseless drivers
    - Electrical protection for over current and over voltage
    - Further improvements on the reliability of the communication protocol

2. Optical and thermal design

- Design and prototypes. Different optical/thermal architectures have been designed and prototyped, and have been benchmarked in terms of colour mixing and output flux. Apart from the main HILED

lamp, featuring more than 3500 lumens, stabilized/controlled full visible spectrum output, 93% light output ratio.

- Thermal-management validation. The housings are evaluated in terms of how efficient is the thermal path from the LED junction to the heatsink. Two particular indicators were monitored: the presence of hot-spots and the junction temperature.
- Life cycle assessment of the different designs. This analysis assists to identify possible problems, from the point of view of environmental compliance, in the selection of the different components.

3. OLED wavelength engineering

Top emitting OLEDs have been optimized in terms of the shape of the emission spectrum. Two different target values were set inside the project for the peak emission wavelength of the OLEDs: 545nm and 565nm. Narrow peak emission with 40nm FWHM were realized for a peak emission wavelength of 545nm. These results have been achieved based on the following steps:

- Emitter material screening for green and yellow emission
- Determination of optical constants
- Optical modelling of light out-coupling
- Adjustment of transport layer thicknesses inside the OLED stack
- Comparison of simulated and experimental emission spectra

A modular device design was developed in order to allow integration of the OLEDs in the combined OLED/LED luminaire. For this, top emitting OLEDs on glass substrate were mounted on a PCB backplane.

The OLED modules were encapsulated using a glass cap. Reliability tests showed that OLED lifetime was significantly improved using an additional thin film encapsulation layer based on atomic layer deposition.

RESULTS FROM TARGETED APPLICATIONS

4. Light for human health and performance

- We have demonstrated that the spectrum of light can be tuned to optimize people's alertness levels, performance, and mood, depending on the time of day and the task required. Wireless feedback from wearable biosensors enables the output of the light engine to be controlled directly by people's physiological state (e.g. heart rate, heart rate variability, and skin surface temperature), maximizing or minimizing the alerting effects of light as necessary.

  In more detail: The ability to sculpt the spectrum of light with the tuneable multi-LED-channel light engine in real-time allows us to selectively stimulate the visual and non-visual pathways. The non-visual pathway responds best to light of short wavelengths, via the photopigment melanopsin expressed by the intrinsically photosensitive retinal ganglion cells. The visual brightness and chromaticity ("colour") of light is determined by the cone photoreceptors. We developed methods to generate variable light spectra with the tuneable light engine, which allow us to trade off the amounts and effects of non-visual ("melanopic") and visual ("photopic") illuminance.

- We have shown that (1) narrow-band "blue" light, at low photopic illuminance, suppresses melatonin levels as effectively as broad-band "white" light with the same melanopic illuminance but

much higher photopic illuminance; (2) broad-band "white" light suppresses melatonin levels much more effectively than "amber" light at the same photopic illuminance; (3) "white" light suppresses subjective sleepiness equally effectively as "blue" light with the same melanopic illuminance, and much more than "amber" light. But, although "blue" and "white" light both suppress melatonin and reduce sleepiness, they do not reduce the effects of fatigue on performance in the evening. Instead, "amber" light increases performance on visual attention tasks. "Amber" light, with low melanopic illuminance and high photopic illuminance, is also rated as more pleasant than "blue" light. Thus, we recommend that, in the evening, to improve mood and visual performance, while allowing melatonin levels to rise naturally, "amber" light with high photopic illuminance but low melanopic illuminance is used.

- We have demonstrated that the light engines can be controlled wirelessly in real-time by the data from wearable biosensors – actigraphs – which is used to monitor people's alertness levels during the "post-lunch dip" in the afternoon. We have shown that changes in light spectra can be triggered automatically when alertness levels decline, and that the resulting increase in photopic or melanopic illuminance does boost alertness.

- The ability to tune light spectra in real-time with multi-channel LED technology allows teasing apart of the visual and non-visual effects of light, and their dependence on the shape of the illumination spectral power distribution. From a series of behavioural experiments in people at different times of day, performing different tasks, we conclude that "***Seeing worse may lead to feeling worse and performing worse, despite being less sleepy."***

- Overall conclusion: Lighting technology in the home and workplaces may soon be modulated in real-time to individual needs, based on data from wearable biosensors, and dependent on circadian rhythm and environment. These will use less energy than the light sources currently on the market.

5. Light for high productivity horticulture

- Young tomato and pepper plants were exposed to blue, green, amber, red, white or a combination of red and blue light by SSL fixtures specially designed and produced by Hortilux Schréder, with considerable effects on plant architecture, biomass and underlying processes such as photosynthesis. That implies that in plant propagation, plants with the desired characteristics in terms of height, plant weight and leaf area could be obtained using the specific spectral composition of LEDs. Plant monitoring and modelling revealed that light of all colours was used efficiently during the photoperiod, although the level of photosynthesis was dependent of the spectral composition. Experiments with variable spectra showed that a short period of green light affected plant architecture, irrespective of the period of the day this light was given. Blue light increased the rate of photosynthesis under sun light conditions, which might be favourable in commercial horticulture where LED light is provided additional to the light of the sun.

- Also, partner IRTA determined that the use of tuneable SSL of high output in plant growth chambers proved useful to assay the effect of particular spectra in tomato crudités to enhance antioxidant content. The results are consistent with the hypothesis that antioxidant content in tomato fruits is related to total irradiance in the 400-750nm range rather than to the specific

spectrum. However, results in Mediterranean commercial greenhouses show still some potential for the use of supplemental blue light to increase lycopene content

6. Light for cultural heritage and museum lighting

By using the 1st and 2nd prototype luminaires, visual experiments were conducted to find the optimal light properties for museum lighting applications, like the optimal illuminance level and correlated colour temperature. Result of the experiments was that for museum lighting a CCT between 4000K and 5000K is most preferred and an illuminance level between 200 lx and 600 lx. Considering the safety of the artwork and the standard museum lighting requirements 200 lx could be used in such applications.

Pigment ageing experiments showed that the most sensitive pigment and binder combinations are those where organic materials are used. In those cases a general yellowing of the colours could be observed. Those changes are proportional with the dose of the harmful irradiation represented well by the CIE Damage Index (DI). By doing spectral optimizations based on the DI artwork safe lights can be tailored. The changes of the aged samples were also investigated by using chemical analysis techniques like the FTIR which could also discover which pigment binder combinations can have photocatalytic properties.

In the final phase of the project the final prototype luminaire could be used for demonstration in the professional art community to find out if the HI-LED concept could be used for conservator and restoration tasks. The result of this trial is that the light quality and the flexibility added to the spectral content selection is remarkable, and the ability to enhance specific colours is of great value in this niche market..

IMPACT AND DISSEMINATION

During the project, great efforts have been dedicated to the dissemination of results. In particular, the results have been presented in 23 international conferences, 11 Journal Papers, and 12 exhibitions and invited lectures. The coordinator IREC has also organized two workshops:

- **HI-LED: Human-centric Intelligent LED engines for the take up of SSL in Europe**, Barcelona 25th of June, 2015

- **The 2nd Workshop HI-LED: "Spectrally-tunable LED and OLED lighting**

The workshop was held in the framework of the LED professional symposium, LpS 2016, in the Festspielhaus of Bregenz, Austria during the afternoon of the last 21st of September. The event was organized under an international perspective and six reputed Scientifics were invited. A Poster session and three different demo sessions were developed. In the event were discussed novel advances in tunable LED and OLEDs and experimental light engines were shown during different short Demo sessions.