Ph.D. Course in Physics – XXVIII cycle - Università degli Studi dell'Insubria

RESEARCH ON A BRIGHT LIGHT SOURCE:
OPTICS, TECHNOLOGY AND EFFECTS ON HUMANS

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Abstract

There are countless reasons why the Sun is essential: one of these is daylight. This light, that comprises both the component diffused by the atmosphere and the transmitted one, is the reference for a naturally lit scene, also being the main synchronizer of our circadian rhythms.

I carried out my research in the framework of two European projects (COELUX and SKYCOAT), coordinated by the University of Insubria, which were related to the reconstruction of natural light indoors.

In such a context, in collaboration with the consortium partners but mainly with the spin-off CoeLux Srl, my research dealt with the bright light source used to artificially recreate the sun, regarding the optical design, the technological implementation and the effects produced on humans.

The approach is interdisciplinary, involving different branches of science as well as technology, psychology and business perspectives. These aspects were analyzed, insofar as relevant, in order to design, optimize, and realize the prototypes.

The actions that were carried out and are reported in this work comprise: the definition of the requirements for creating a valid light source, a review of the state of the art related to the areas of interest, the development of a solution meeting all the requirements and the characterization and testing of the prototypes.

The LED-based light projector that includes the results of this work perfectly suits the CoeLux technology and is a cornerstone in the study of effects on humans.

Sommario

(Italian abstract)

Il Sole svolge diverse funzioni per cui è fondamentale, e fra queste vi è la generazione della luce diurna. Questa illuminazione, che comprende sia la componente diffusa dall'atmosfera, sia la componente trasmessa, è il modo più naturale di illuminare la scena, e funge anche da sincronizzatore principale per i nostri ritmi circadiani.

Il mio percorso di dottorato si è svolto nel contesto di due progetti europei (COELUX e SKYCOAT) coordinati dall'Università dell'Insubria, incentrati sulla ricostruzione della luce naturale in ambienti interni.

Ho svolto la mia ricerca in collaborazione con i partner del consorzio, e principalmente con lo spin-off accademico CoeLux Srl, riguardo la sorgente luminosa brillante utilizzata per ricreare il sole, in particolare riguardo gli aspetti di progettazione ottica, della implementazione tecnologica e degli effetti prodotti sugli esseri umani.

L'approccio è stato interdisciplinare, richiamando varii rami della scienza, la tecnologia, la psicologia ed anche diversi temi commerciali, per quanto utili a progettare, ottimizzare e realizzare i prototipi.

Fra le azioni intraprese che sono riportate in questo lavoro, vi sono in particolare: la definizione dei requisiti per ottenere una adeguata sorgente luminosa, l'analisi dello stato dell'arte dei temi legati a questo lavoro, lo sviluppo di una soluzione che rispondesse a tutti i requisiti ed infine la caratterizzazione dei prototipi e lo svolgimento dei test necessari.

I risultati di questo lavoro hanno contribuito alla realizzazione di un proiettore luminoso a LED che si integra perfettamente con la tecnologia CoeLux e che è elemento cardine dello studio riguardante gli effetti sugli esseri umani.

Acknowledgements

Secondo i disegni del buon Dio, sono poche le cose che si riesce a fare totalmente da soli; normalmente piuttosto è necessaria la compagnia di qualcuno. E quando c'è una compagnia su cui poter contare è bello riconoscerne il valore e ringraziare.
Molto spesso poi, oltre alla compagnia, vi sono anche sostegno e correzione.
Alla conclusione di questo percorso durato diversi anni, quindi, colgo l'occasione per ringraziare chi ha condiviso con me in questi modi il cammino, o anche solo una sua parte. Sperando di dimenticarne pochi, riporto qui sotto alcuni ringraziamenti, e nel farlo ancora una volta mi rendo conto che dovrei farlo più spesso, visto quanto è piacevole.

---Parte 1---
"sky and sun, a lot of fun"
(Paolo Ragazzi, in un momento poetico durante gli anni di dottorato)

Anzitutto il supervisore di questo mio dottorato, prof. Paolo Di Trapani.
Grazie a lui in questi anni ho visto e imparato molte, moltissime cose (Shakespeare direbbe: "Ci son più cose in cielo e in terra…"). Per diversi motivi dovrei ringraziarlo, sia attinenti all'ambito della ricerca qui esposta che a numerosi altri ambiti.
Quanto a questo lavoro, è stato certamente, giustamente e positivamente influenzato da Paolo, e io sono grato di questo. Volendo sottolineare due aspetti, il primo è legato alla sua personalità: stupefacentemente vulcanica e tenace. Questo fattore emerge indubbiamente, soprattutto per chi lo conosce, da questo lavoro, almeno sotto la prospettiva della creatività e multidisciplinarietà, ma anche dal fatto stesso che questa ricerca non si è arenata nelle difficoltà incontrate durante gli anni. In secondo luogo, lo ringrazio perché nella sua originalità e unicità ordinariamente condivide con i suoi interlocutori una mole imponente di spunti di lavoro interessanti, spesso arrivando a coinvolgerli profondamente nel suo pensiero e intento, e così è capitato anche a me.

Un'altra persona di fondamentale importanza in questi anni è stato Davide Magatti. Non solo perché ho avuto la fortuna di condividere con lui praticamente ogni parte di questo lavoro giovando della sua competenza, ma anche per il sostegno nell'ordinarne tutti gli aspetti, da quello tecnologico a quello logico di sviluppo del lavoro. Questo si vede anche dal fatto che in diversi punti è ovviamente citato anche lui in quanto contributore. Principalmente però lo vorrei ringraziare per il suo ruolo di sostegno e di guida in una grande quantità di occasioni e azioni, spronandomi a fare al meglio la mia parte, e portando avanti la sua con dedizione e cura che ho ammirato.

Per molte, davvero molte, altre persone riservo poi una gratitudine che non può trovare spazio esplicito in questa pagina. In alcuni casi il contributo è stato minimo, in altri molto specifico, talvolta è stato "solo" un incontro professionale. Alcuni voglio citarli esplicitamente: Giorgio G., Antonio L., Marta P., Vasco M., Elena M., fra quelli presenti a Lomazzo nei vari anni; Wilfried P., Markus L., Markus C., dal Tirolo; Andrea P. per le lunghe telefonate tecniche, le tigelle, lo gnocco fritto e anche l'elettronica; Francesco C., Giovanni M., "tecnici" che mi hanno insegnato molte cose con uno sguardo amichevole.

---Parte 2---

"... l'appartenenza è un'esigenza che si avverte a poco a poco
si fa più forte alla presenza di un nemico, di un obiettivo o di uno scopo ... "
(Canzone dell'appartenenza, G. Gaber)

Ci sono altre persone che non hanno avuto rilevanza nel dettaglio specifico di questo lavoro scientifico, ma sono le fondamenta e l'essenza sulle quali è cresciuto (Gaber, nella citazione più sopra, dice dell'appartenenza che si avverte alla presenza di uno scopo…).
In verità, io credo che anche questi, chi più chi meno, possano apprezzare il contenuto del lavoro. Ma grazie a Dio sono molte le cose interessanti nel mondo e forse questo lavoro non lo leggeranno mai, ma questo non è grave. Invece, l'importante per cui voglio ringraziarli è la compagnia nel cammino sulla strada della mia vita.

A questo punto potrebbe sembrare più una dedica, perché quanto scritto sotto certamente suona molto differente dalla prima parte. In realtà, è una parte complementare e questo è forse più comprensibile riportando un'altra citazione a me cara, che lascia intravedere anche lo scopo ultimo di questi ringraziamenti, sperando che siano una piccola musica:

"… tutta la musica è una strada di luce, che porta a Te, amico mio" (Desire, C. Chieffo)

A Beatrice, che ha liberamente scelto di condividere con me il cammino della vita: che bello viaggiare insieme su questa strada.
Alla piccola Agnese, che mentre scrivevo questa tesi piangeva e sorrideva, dando il giusto contributo per la sua età.
Al mio papà che mi educa e mi insegna tante cose, e alla mia mamma, che mi vuole bene da quando sono nato, e anche da un po' prima.
A tutti i miei fratelli, cognati e nipoti (ed anche i suoceri): che bella famiglia!

A tutte le persone, consacrate o no, che mi hanno spalancato lo sguardo! Quella che è "introduzione alla realtà totale" merita per forza di essere citata qui e, anche se non cito le persone, provo un'enorme gratitudine e affetto per chi, in moltissime occasioni e svariati modi, ha contribuito alla mia educazione. Grazie!

Infine, è stupendo fare cose belle, come cantare o andare in montagna, ma è necessario alla vita avere una certa compagnia, quell'amicizia che "ha un unico interesse: il bene e la felicità dell'altro" ed è un'amicizia cristiana.
Quindi devo proprio ringraziare "gli amici", ed è una categoria che per grazia raggruppa tante, tante, tantissime persone, oltre a "i miei più cari amici" (che cito così, un po' velocemente, ma non si sentiranno sminuiti), perché includerei tutti quelli con cui ho condiviso almeno un momento di verità. E li ringrazio per questo.

"… l'appartenenza è avere gli altri dentro di sé"
(Canzone dell'appartenenza, G. Gaber)

Ottobre 2019

Preface

The present document contains the material which concerns the work conducted during my Ph.D. course. The main aim was the development of a complex light source, able to artificially recreate the Sun, the framework being two European projects[1] related to the reconstruction of natural light indoors. Moreover, a third European project[2] is mentioned and is related to the demonstration of the cited activities. Thus, my activity mainly consisted in collaborating to the development of the CoeLux technology as per the agreements[3] between the University and the Company (academic spin-off of the University), sustaining the business development by means of the academic competences. The topics were planned in the Grant Agreements of the projects, and were under the responsibility of the company, that coordinated the activities of the tasks related to the design of the optical systems and light sources, their optical and electrical testing, and their impact on comfort and wellbeing. In detail, within the SKYCOAT project, I worked together with project partners on the following tasks: T3.1 "Specifications, concepts, detailed design of projector and luminaires", T3.3 "Measurements and final design of projector and luminaires", T5.4 "Testing and validation", and T8.3 "Impact measurements on comfort and wellbeing".

My contributions were, for example, in the contextualization and analysis of the concepts as well as in deepening the comprehension of the technology, maintaining a scientific approach. At the same time, I participated in the optimization process for the choice of the LED, and of the optical design. I was also involved in the measurements campaigns which characterized and supported the certification of the light source. Furthermore, the studies on the effects on humans accomplished the requests of demonstrating the effectiveness of the CoeLux lighting.

Notwithstanding the above, and in addition to the topics listed, during the fourth year of my PhD, i.e. after the termination of my University scholarship, I have been working as CoeLux employee at an important application of my research: the development of a new product - "The Moon". This application exploits the bright light source for creating a spectacular nighttime scenario, featuring a nocturnal deep sky illuminated by the full Moon. Through the same window, the still direct light of the Moon bursts into the room, illuminating objects and creating their shadows, which remain still faintly blue colored and illuminated by the nocturnal light of the blue sky. The topic is described in the dedicated chapter, where reference is made also to the CoeLux patent application that I have made.

It is worth noting that the first part of this thesis goes beyond a literature review or a background information collection, as the technology needed a novel interpretation – not yet existing – related to different categories among which atmosphere optics, lighting, perception, architecture, building science and health and wellbeing.

As a consequence, my research mainly involved optical and technological areas of academic and manufacturing fields, taking advantages of the competences of the entire team. At the same time, other scientific branches of research and industrial approaches have been found to be essential to give a complete view on this topic. Going beyond physics, this document invokes, for example, research fields related to the perception and to lighting business, trying to integrate these in the development of the work.

The result is an interdisciplinary work where some topics are significantly more analyzed than other of comparable scientific interest. Despite this, a reader who is a physicist, as the author is, should be favored in following the flow of the text. However, for every topic some fundamental references are cited to support the comprehension.

Finally, it is worth noting that there is room for a deeper understanding of the subject of this work, for example scouting new possible medical perspectives (here only briefly mentioned) that require further studies. I believe that the present work is of interest for any reader, be he/she a physicist or not.

Additional notes:

CoeLux® is a registered trademark, however, the "®" symbol has often been dropped in order to simplify the reading. The usage of the proprietary material has been authorized by the company.

I am grateful for the professionalism that supported this activity, in particular in the persons of Prof. Paolo Di Trapani and Dott. Davide Magatti.

I am grateful for the comments from the reviewers which helped me in producing the final version.

The contents of this work fairly reflect the work I have done and my opinions on the scientific and technological value of the cited topics.

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[1] COELUX [Project ID: 262539 ; Funded under: FP7-SME]
SKYCOAT [Project ID: 310483 ; Funded under: FP7-NMP]
both coordinated by the University of Insubria

[2] DeepLite [Project ID: 606395 ; Funded under: FP7-SME]
where the University was a project partner

[3] Among which the Grant Agreement, and the Consortium Agreement which regulate the partners contractual rights and obligations with reference to each European Project and the *Convenzione* between CoeLux Srl and the University which regulates the relationship between the two institutions.

List of abbreviations

CCT	Correlated Color Temperature
cd/m^2	candelas per square meter - unit of luminance
CIE	Commission internationale de l'éclairage
CRI	Color Rendering Index - where R_a is the average value and R_9 is the index referring to red colors
D_{uv}	Distance from the Planckian locus in chromatic coordinates (u;v)
EMC	ElectroMagnetic Compatibility
HCL	Human Centric Lighting
K	Kelvin - unit of the color of white light (refers to CCT)
L_B	the blue-light weighted radiance (using the hazard function, $B(\lambda)$) as defined by EN62471
LID	Light Intensity Distribution
lumen	unit of luminous flux
lux	unit of illuminance
MAE	Mac Adam Ellipse

Table of Contents

Nature and CoeLux

1 - Field of work

The purpose of CoeLux technology is the reproduction of natural light, by means of complex optical systems; the actual, artificial, source which provides the power to the system plays the role of the Sun: this is the main subject of this research.

The connection between CoeLux and nature is the first pillar of this work, the second one is the technology that is associated with this product, and the third pillar actually is the relation between light and human beings. The approach is multidisciplinary, including methods and considerations typical of branches of knowledge other than physics; in fact, I believe that doing so, this work gains an increased value in terms of usability and usefulness. For a specific approach that reviews in depth the details related to this work in the specific field of physics or lighting design or medicine, the best way, as a matter of fact, would be to take a single part of this work and, at the same time, refer to specific and up-to-date scientific essays.

As exposed in the following chapters, there is a multitude of different light sources on the market, in particular those powered by electricity, but none of these work exactly as needed in this research, mainly because the requirements derive from the CoeLux technology particular features. Notably, there are significant complexities from a technical point of view, and, additionally, only a truly tailored design allows for the optimization of performances, both on the optical side and concerning functionality. Finally, to support CoeLux products in an effective way, the light source should suit the requirements of the appointed market target, in terms of performances and cost.

In this work emerge here and there analysis of some aspects of the lighting industry (typical products characteristics, market standards, available technologies...), the comprehension of these being the logical starting point of a research work about a new light source. Commercial products, trade shows, business magazines, builders and also designers and governments, all specify these aspects even up to technicalities, in an adaptation process that reflects technology advancements, resources optimization, new functionalities and wellbeing research.

As it will be exposed in detail later, the artificial Sun is one of the key components of the CoeLux systems, as it is the “engine” that makes the system working: it gives the energy whose effects are seen up to the lighting of the room. At the same time, its design demands for optical characteristics able to convince people till the impressive perception of a natural scene.

In this chapter the principal themes of this work are presented in a synthetic way just to give an overview, whereas some topics are discussed in depth in the following parts.

a) Scenery

This research is also a part of three EU-funded projects: COELUX, SkyCoat and DeepLite, in which the University of Insubria and CoeLux were partners (CORDIS, 2016). Here below the scenery of this research work is reported, using also the description of the cited projects.

The quality of artificial illumination is a major concern for living and working spaces that have no windows to bring the added comfort of visual contact with the external environment.

The problem of how artificial lighting affects the quality of life is particularly relevant for areas designed to host different types of human activities that span over a range of many hours (e.g. offices, or rooms inside residential buildings). In addition, in some cases, the presence of windows is even not allowed, thus preventing livability and generating psychological constraints (e.g. underground architecture, elevators…). Another considerable circumstance are architectures located in countries where sunlight is missing for many months of the year.

In such a context, COELUX fills this open gap in the lighting market: providing a unique, unexpected view of a comfortable sunlit sky.

With EU funding of the project SkyCoat (Sky like coating materials for hypogeal and skyscrapers architectures), project members sought to recreate in the underground the experience of natural light from the Sun and diffused sky lights. Reproducing daylight in hypogeal spaces dispels any negative psychological emotions and opens new territory to real estate investors, architectural and lighting designers, and the public.

The effect of sunlight -which is warm, directional, and defines volumetrically the geometry of objects- combined to the effect of skylight -diffused, cold, soothing, capable of endowing shades with a soft blue tinge- has a unique role in the relationship that human beings develop with architectural spaces.

b) Some key factors

Nature and lighting

The expertise of lighting evolved during centuries developing different light sources. The illumination perceived as the most natural is daylight, combustion being the first historical available light source. Humans used fire to light the night, but also to heat and protect themselves, and later for a multitude of applications. Then the human being evolved in relation with fire, our brain recognizing its light as that of the night, and preparing the body to sleep. At the same time, there is a long history of different fuels used (above all mineral, vegetable or animal oil), while the introduction of electric light happened in the 19th century (Williams, 1999).

"Light affects us both physically and biologically – and you'll find the explanation to this seven million years back in time. […] The daylight on the African savannah is bluish and it was in this light that our ancestors hunted and collected. It became, and is still perceived as, our "working light"" (Bergman, 2016).

It is worth noting here that light is a well-known characteristic of Nature, in the sense that humans immediately recognize whether the physical quantities correspond to what is expected. In this perspective, it is interesting to note that natural sounds are also imitated and to a better extent, using high fidelity system and appropriate contents; interestingly, reproduction of sceneries are diffused (e.g. pictures) but a lack of natural light is evident. The need of a new light might be interpreted with respect to what said before, in a continuous attempt of achieving a pleasant light.

Finally, and linking with the word pleasant just used, it should be noted that also from an artistic point of view, natural light (as well as a natural, open air, scenery) is linked with the peculiar beauty that only nature can produce. At the same time, is the sole lighting source which allows a lot of art forms to express at their best (e.g. sculpture).

Energy saving

It is well known that energy saving is an important theme (in particular very popular during the last century), and it is known that LED are useful in the sense that allow for a significant efficiency improvement[1]. A milestone in these reasoning is, of course, the Nobel Prize in Physics jointly awarded to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura (2014) "for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources".

[1] "LEDs are, in principle, capable of generating white light with a 20 times greater efficiency than conventional light bulbs. Deployed on a global scale to replace conventional sources, such solid-state light sources will result in enormous benefits that, over a period of 10 years, include gigantic energy savings of 1.9×10^{20} joule and financial savings exceeding a trillion (10^{12}) US$." (Kim & Schubert, 2008).

The Sandia Report SAND-2000–1612 (2000), for example, about the introduction of LED light sources reported: "The global savings would be more than 1000 TWh/yr of electricity at a value of about US$ 100B/year" (Haitz, Kish, Tsao, & Nelson, 2000).

A different approach on the energy saving theme is that one related to daylighting: an interesting reference is (Ellis, Handly, McEachron, Del Risco, & Baynard, 2011). As also summarized by Veitch in the IRC Internal Report No. 659: "The energy-efficiency of natural daylight is unbeatable. Where possible, this lighting source should be incorporated into the lighting design, […] because it is "free" light delivered in a form that is preferable to most people (e.g., Heerwagen & Heerwagen, 1986)" (Jennifer Ann Veitch, 1994)

At least two more characteristics should be cited at this point with regards to savings; these are not explored in this work but are however strictly related to this, and concern different dimensions where savings might be improved:

- Timing: switching cycles can be implemented
- Spatial: light should be directed only where necessary

Notably, these features can easily be controlled when LED sources are used (thanks to the very fast switching time) and directional optics are integrated. The result of the present work is in principle adequate to support those, particularly speaking about a directional beam (the sunlight) which do not annoy thanks to the presence of a diffused background (the skylight) and succeed in this point in the most natural way!

Light for humans

Light impact on humans may be collected in three categories: Visual, Emotional and Biological.

The first one is, in fact, what allows us to look at the reality, the possibility to identify different objects as well as to interpret our interlocutor reaction. By the way, it is interesting to note that not even we see the single scene (as a static picture), but vision is of critical support during the interaction with the reality and is a fundamental and always active way of learning.

The second category of the effects of light on humans actually acts on our emotional state by means of the different representations of the scenery we may meet, and is related, at least in part, to the artistic dimension of the light design.

The last category comprises the entirety of actions of the visible light on human body that we cannot immediately reveal by vision. While the previous categories somehow referred to what is seen, in this case there may be no image or visual impression at all (as it happens when getting burned by the UV Sun rays). Visible light (thus excluding UV and IR radiation) in fact might hurt humans only in few cases, involving very bright emissions or coherent radiation. Then, this category comprises the biological responses of the human body to the lighting conditions, as, for example, the regulation of the circadian internal clock (Rea, 2002; Tosini & Menaker, 1999; Wurtman, 1968, 1975).

Veitch summarizes that these effects "fall into three general categories. First, the bactericidal effects […]. Second, light absorption through the skin produces both local and systemic responses. Local responses include suntan and sunburn; systemic responses include vitamin D metabolism […]. Third, light incident on the retina produces neural signals that influence hormonal processes." (Jennifer Ann Veitch, 1994)

On the other hand, there is the possibility of referring to “perception”; the citation reported gives an interesting insight.[2]

It is worth reporting here also the observation by Cuttle: “Under normal daytime lighting, two-way interactions occur […] there is the process of recognising object attributes that are revealed by the lighting patterns, while at the same time, and working in the opposite direction, it is the appearance of these lighting patterns that provides for the viewer's understanding of the light field that occupies the entire space.”(Cuttle, 2015)

Moreover, as written by Flynn J.E. (Flynn, 1977): “[…] priorities should begin with the overall user well-being, the visual quality of a room, and should not be limited to task visibility and other somewhat mechanistic arguments”.

A considerable attention is now devoted in the scientific community to properly investigate this field: some aspects are known and there are new metrics proposed (Rea, 2015), but in fact there is room for going in a deeper understanding (Cao & Barrionuevo, 2015; Figueiro, 2014; Ticleanu & Littlefair, 2017). Beyond this, for centuries lighting has been treated in a spontaneous way even foreseeing its beneficial effects. Nowadays, research is meritoriously followed by regulations as well as best practices. In the following chapter a short review is shown about it.

[2] “Perception is inherently idiosyncratic. […] the brain receives information about the outside world through sensory organs—in the case of visual perception, the eyes. In primates, the information coming from the retinae is interpreted by a large network of highly interconnected visual areas. Thus, it should not come as a surprise that the interpretation of this information by the visual system of any given individual - infused with plenty of extraretinal information - does not necessarily correspond veridically to conditions in the external world or the interpretation of other observers.” (Wallisch, 2017)

2 - Sun and Sky: the natural light

During the day, the natural light illuminates the world: the term "daylight" refers to the entire variety of different lighting conditions. However, this category of lighting is by far considered as *the* reference: beyond the appropriateness of such light to any task, which would be fanatic to assert, it is easy to state that it is the innate lighting that people expect for living and judge as pleasant.

The scientific descriptions of daylight swing from simplified visions to complex descriptions; however, two are the main actors and these are considered in this work: Sun and Sky, and here is a short recap of the main aspects of these two pillars.

Sun is the paramount radiation source: it illuminates the scene, it is the main source of energy for organisms, and its light has been recognized as necessary for the human body through the centuries, finding also healing applications (e.g. Nightingale studies) (Nightingale, 1860).

While the Sun, being a star, involves nuclear reactions and a huge quantity of energy production, the sky light is related to a simple diffusion by a transparent material: the air, the atmosphere, being a passive light diffuser.[3]

For a comprehensive treatment of the natural optical phenomena in the atmosphere two masterful books are the reference: the first one by Minnaert and the second one by Lynch and Livingston (Lynch & Livingston, 2001; Minnaert, 1994).

With respect to its importance in lighting, Bouma suggested daylight as the preferred reference source (Bouma, 1948): "It (daylight) displays a great variety of colours, makes it easy to distinguish slight shades of colour, and the colours of objects around us obviously look natural".

It is worth only touching here the fact that beyond the apparent relation with vision and the effects of the radiation on the skin, some other retinal cells respond to daylight also mediating neuroendocrine effects; as analyzed in the following chapters, this is a reason contributing to the value of daylight.

[3] For the current description, phenomena like the airglow, chemiluminescence or fluorescence of the air (and many other occurring in the atmosphere) are not considered, these being some order of magnitude less visible than the Rayleigh scattering which creates the blue tinge.

a) The Sun: a huge source of light and energy

The Sun is a huge source of energy and it is abundantly studied by different physical branches. Here are recalled just few basics information about it in the perspective of this work.

It is widely known that the radiation coming from the stars is well approximated by the blackbody radiator formula (Planck's law), allowing for a synthetic description of the total spectrum emitted by the Sun.[4] It is worth recalling here also the fact that the Planck's law gives the absolute radiance of a black body, thus defining also the luminance; from simple physical considerations, and considering the geometrical conditions, the actual power and luminous density can be calculated. For what concerns the Sun irradiance, a common reference is set considering the sun light before passing through the atmosphere, when the air mass coefficient is equal to zero (AM0). In this condition, the light coming from the Sun onto the Earth reaches a power density equal to 1367 W/m^2. Obviously, this number is just for reference and the real value changes in function of the actual distance between the Earth and the Sun, and depends on the Sun activity. One may refer to this irradiance as to the external irradiance.

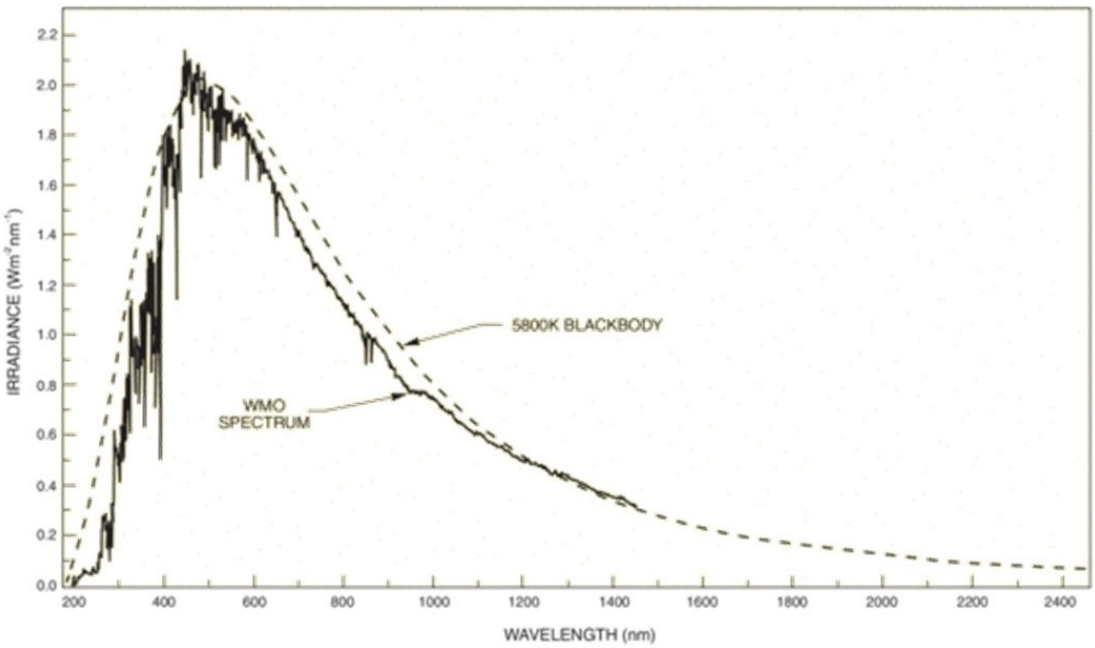


Figure 1 - Solar spectrum before impinging on the atmosphere compared with the theoretical blackbody emission curve (5800 K). Image from Newport website[5]. Here the AM0 spectrum reported is that one adopted by the World Meteorological Organization (more recent spectra slightly differ from this one)[6]

[4] In Figure 1 are plotted the real spectrum of the Sun and the fitting Planckian curve (5800 K). The most noticeable difference between these curves is the presence of the spectral lines due to the absorption by the cool gas in the outer region of the Sun (the so called "Fraunhofer lines") (Böhm-Vitense, 1989)
[5] https://www.newport.com/t/introduction-to-solar-radiation
[6] A complete analysis about this is available at https://rredc.nrel.gov/solar/spectra/am0/

Notably, the energy contribution from the visible part of the spectrum is approximately 45%, and the infrared radiations carries approximately a similar part of the energy, whereas the UV portion of the spectrum account for only a minor part[7]. Thus, it is easy to argue that the luminous efficacy of the Sun is actually low: indeed, the full spectrum produced is well-peaked on the luminous function (eye sensitivity) but it is broad, in particular:

- there is a huge emission in IR photons
- the emitted spectrum covers the entire range of visible wavelength, even the spectrum regions where the eye sensitivity is low, thanks to this feature giving also a perfect color rendition

In the perspective of this work, the most important characteristics of the Sun are the following:

- Light emission: black-body radiation with effective temperature equal to 5800 K
- Subtended angle from the Earth: approx. 31’ (approximately half a degree)
- Luminance exceeds one billion of candelas per square meter

Moreover, the Sun is a unique light source from a lighting point of view for at least two additional points:

- it emits light approximately uniformly over the emitting surface
- its characteristics remain approximately constant over an enormous timespan (an expected lifetime of billions of years)

All these features will be used for considerations about the CoeLux natural imitation.

As sketched above and visible in Figure 2, from (Stine & Geyer, 2001), the small subtended angle is simply a consequence of the Sun distance, and the high directionality of the sunlight is obtained just by geometrical propagation and selection of a small portion of the total light emitted, namely the light that impinges on the Earth. Notably, this interesting feature of “collimation” is obtained “wasting” energy, *i.e.* spreading everywhere in the space its rays, because the Sun is, in fact, an omnidirectional emitter and 99,9999999 % of the light it produces does not reach the Earth. It is important to note this feature because from an optical point of view this is the easiest method to obtain a directional uniform light beam. As a reference, artificial light sources should take into account a large use of optics to obtain such a directionality (and be efficient at the same time), only laser sources can reach these

[7] This is true both for external irradiance and for the spectrum reaching the Earth surface: effects such as back reflections, scattering and absorption related to the presence of the atmosphere, have only a slightly effect on the ratio between **UV, visible light and IR**. Using the data reported in the standards ASTM E490 and ASTM G173-03 (extraterrestrial solar spectrum and direct+circumsolar irradiance, reported at https://www.nrel.gov/rredc/), respectively the three electromagnetic radiation bands constitute the spectrum energy as follows (**UV - vis – IR**): @AM0 (**11% - 42% - 47%**), @AM1.5 (**4% - 46% - 50%**)

characteristic of collimation inherently, thanks to a different light generation principle (stimulated emission).

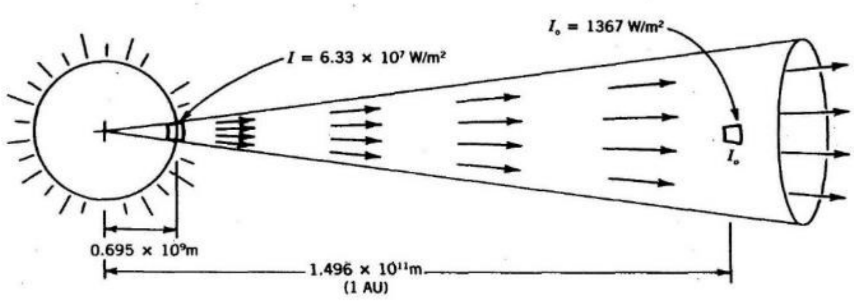


Figure 2 - Sunlight directed onto the Earth, collimated just because of distance (image from "Power from the Sun" by Stine & Geyer, 2001)

The cited directionality, together with the high brightness, perceptually describe what is usually referred to as "the sun beam" or the collection of sun rays. In fact, the real Sun is easily recognized by our brain from these features and from the fact that it is actually perceived at an enormous distance.

b) The Sky: optics and colors

While the Sun is the principal and actual light source, daylight is constituted also by skylight, caused by the diffusion of a part of the light coming from the star. Atmosphere optics is a complex subject, not treated here, whereas the main phenomenon, the Rayleigh scattering is below summarized. The variability of real conditions, caused by the presence of water vapor, changes in atmospheric pressure, aerosol scattering and absorption, in fact creates a multitude of effects well treated in a number of books and papers (Hernández-Andrés, Lee, & Romero, 2003; Lynch & Livingston, 2001; Minnaert, 1994; Preetham, Shirley, & Smits, 1999) just as an example.

The Sun-Earth distance, cited before, critically contribute to the skylight realization (and thus also to daylight realization). Firstly, it should be noted that the considerations regarding the directionality of the sunbeam are an input condition for what concerns the phenomena described here below (otherwise the mixing of different scattering directions should be described). Secondly, the distance is important because, when looking at the celestial hemisphere, a small portion is occupied by the light source, whereas the remaining area is fundamentally dark (beyond the atmosphere) considering the low brightness and faint visibility of the other stars. This fact dramatically enhance the contribution of the light from the sky, given the fact that the two light sources (Sun and Sky) are visibly distinguishable.

As cited before, there is a multitude of scattering centers in the atmosphere, but even in a pure air there remain the fundamental phenomenon named after Lord Rayleigh. Scatterers are the nitrogen and oxygen molecules in the atmosphere, providing for a stronger diffusion of short wavelengths than for the longer. Then, of course, it is important to note that violet (more strongly scattered than blue) is less visible to our eyes[8]. It is worth also noting that obviously the entire spectrum is diffused, and the "bandwidth" is clearly broad.

An historical debate should be cited here which is about the scattering centers, arguing whether molecules itself or density fluctuations act as diffusers (for reference one can read, for example (Bohren & Fraser, 1985)). Basically, the fundamental pillar is that the dimension of the scattering center should be small, at least 1/20 of the wavelengths involved, other additional assumptions are reported in the cited texts (Bohren & Huffman, 2008; Kerker & Loebl, 2016; Rayleigh, 1899; van de Hulst, 1957).

In principle the transmittance can be retrieved by the Lambert-Beer law. The reported formulas from (Kerker & Loebl, 2016), instead show the extinction cross section per single particle. In these, λ is the vacuum radiation wavelength, θ is the scattering angle (the angle between the directions of propagation of the incident and scattered radiation), d is the particle diameter having n_2 refractive index. The medium refractive index is indicated by n_1 and D is the effective diameter, equal to n_1 per d. Finally, m is the optical mismatch between particle and medium (n_2/n_1).

$$\frac{d\sigma}{d\Omega}(\theta, \lambda) = \frac{\pi^4}{4}\frac{D^6}{n_1^2\lambda^4}\left(\frac{m^2-1}{m^2+2}\right)^2\frac{(1+\cos^2\theta)}{2}$$

Equation 1 - Differential cross section

$$\sigma(\lambda) = \frac{2}{3}\pi^5\frac{D^6}{n_1^2\lambda^4}\left(\frac{m^2-1}{m^2+2}\right)^2$$

Equation 2 - Total extinction

In Equation 1 is shown the differential scattering cross section, whereas in Equation 2 the total extinction is reported. It should be highlighted that the dependence of scattering cross section on the sixth power of the diameter cause large particles being much more efficient than small particles, increasing efficiency of diffusion and involving, when increasing size too much, deviations from the Rayleigh regime.

[8] For reference, considering 420 nm for violet radiation and 450 nm for blue, as reported in the technical international standard ISO 11664, the ratio between the eye sensibility at these wavelenghts is around 1/10.

These equations synthetically express a number of dependencies: both Equation 1 and Equation 2 follow the very well-known λ^{-4} law (which determines the blue color of the sky), and also exhibit the same *m* and n_1 dependences.

The following image (Figure 3) naively show the scattered spectrum when the light source is the real Sun. This measure was taken near Milano (Italy) by me; the used instrument is the spectroradiometer SpectraScan PR-655 by “Photo Research Inc.”. Notably, the proprietary software (SpectraWin) reports on the graph (near y-axis) the label “Radiance”, whereas the spectral density of the same should be expressed in $W/sr/m^2/nm$, the radiance being the total (over the entire spectrum) radiant power emitted per unit solid angle per square meter. For the reported spectral measurements, however, no reference is directly done to radiance obtained from these measurements. In other crucial points of the work, the luminance instead is reported, which was obtained using the same instrument.

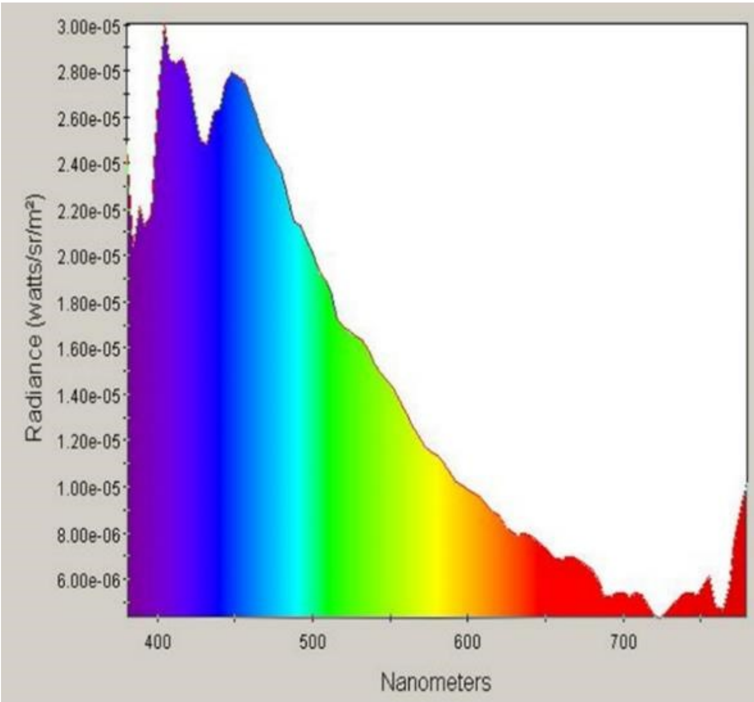


Figure 3 - Skylight radiation

It should be noted that, in the Rayleigh approximation, the scattered color does not depend on the angle, thus being constant in every direction. On the other hand, the intensity slightly depend on θ.

It is easy to observe that the Rayleigh scattering is exactly the reason why the sky is blue tinged. In linking with the next part of this text, it is worth citing here explicitly the paper which collects some of these observations and actually reports a basis for the work that followed. This was published in 2011 from Magatti et al. "Colors of transparent submicron suspensions on approaching the Rayleigh regime." (Magatti et al., 2012)

3 - CoeLux idea and technology effectiveness

CoeLux® is a scientific breakthrough, allowing you for the first time to reproduce in an interior space the physical effects and optical phenomena of natural light, specifically the diffusion and transmission of sunlight through the atmosphere. CoeLux® technology recreates the sun and sky allowing you to truly experience the outdoors while indoors (CoeLux, 2014).

CoeLux® technology actually reproduces the lighting outcomes and the lighting appearance of the natural light as perceivable by humans from an aperture in a room. This means that only some optical parameters are taken into account for the reproduction (and not the entire physical system). On the other hand, the effects of this optical and lighting design swell beyond a pictorial view, giving exactly the feeling of viewing the real Sun and Sky, and not, for example, a picture of these.

The native idea of CoeLux came years before this work and is related to some scientific laboratory experiments aimed to the reproduction of the physical phenomenon of Rayleigh scattering. Once the experiments were realized (Figure 4 show a scattering experiment carried out by me in 2010) the divulgation took part, involving both the scientific community and the common people publication and distribution (diluceinluce.eu, 2007; Magatti et al., 2012; Ragazzi, 2010).

Figure 4 - Light scattering experiment in laboratory

The most creative step has been the comprehension of the following potential idea: turning the laboratory experiments in a lighting technology, the vision of the actual result (at that time only potential) just looking at the reproduced physical phenomenon.

There are many practical differences between an experimental setup and a product: while some characteristics might not require an implementation (in this case I can mention the colors diffused by physical sample), some other might be completely wrong-sized, whilst some lacks might be apparent or some potential error hidden. It is easy to understand how a single chip LED, useful for laboratory experiments cannot fulfill the requested amount of light for a room in any home.

However, this creative step, while non-obvious, has been supported by at least two pillars: one is the eye which is a powerful instrument, and the second is a trustful attitude. Specifically, the paramount simplicity of using vision enormously encouraged the attempts made in order to reproduce the phenomenon exactly as seen in the experience. Regarding the attitude, it is easy to recall here what happens in every adventure: to reach the objective a strong perseverance is needed, and the continuous need of energy is solely pleased by the confidence that the objective is actually reachable. One can say that the CoeLux birth has been somehow an adventure. I participated to some of the preliminary steps described and with this work I relate on the contribution given on the bright light source; the entirety of CoeLux growth has been conducted by prof. Di Trapani and a number of people collaborated to that, including project partners.

Three are the key elements involved in the natural lighting, and of course these could be find also in the laboratory experiments cited before: the light source, the distance between the Sun and the Earth, and the scattering element. It is intended that these elements sequence describes also any CoeLux system.

Figure 5 - Demonstrator of two-sources-by-scattering concept (laboratory experiment)

It is obvious that the order of magnitude of some physical quantities involved is by no chance reproducible (e.g. the star dimension and distance), on the other hand these conditions may be not necessary. In fact, our brain is not able to measure, just by vision, that the Sun is 150 million Km away, it simply sees that it is indistinctly far, because of perspective and focalization, and that it subtends a certain angle to our point of view.

a) Human Centric Lighting?

CoeLux technology is a different way of lighting from other artificial lighting technologies, as will be discussed in the next chapter. This fact is intuitive when looking at real pictures taken in indoor spaces where such systems are installed.

The "Human Centric Lighting" expression, which is frequently used today, aims at highlighting also the fact that the light on humans has a range of effects, as described above. Thus, lighting a space can heavily affect humans, and a diligent design should take into account the fact that sleep, alertness, performance, and wellbeing, and other conditions of the occupants might depend on the quantity of light, the spectrum, as well as timing, duration, and distribution of the same (see for example (P. Boyce, 2004; J A Veitch & Galasiu, 2011)). Moreover, different conditions such as jet lag, Alzheimer's disease, insomnia, and depression might be improved. Evidences of these facts exist but it is worth noting that the complete panorama is not yet well established, for reference see, for example, following ref.(Bhattacharjee, 2007; Figueiro & White, 2013; Harb, Hidalgo, & Martau, 2015; Hobday, 2016; Leichtfried et al., 2015; van Ee, Van de Cruys, Schlangen, & Vlaskamp, 2016).

From an historical perspective it should be noted that there are proofs of these effects of light being studied during the centuries: examples are the heliotherapy from Hippocrates as well as the recommendations for hospitals by Florence Nightingale (see also (Hobday, 2008)). More recent "medical" examples can be the papers from Castro et al. reporting on effects as revealed in ICUs (Castro, Angus, & Rosengart, 2011) as well as (Acosta, Leslie, & Figueiro, 2017). Regarding other applications, a dated paper by Veitch, Gifford and Hine reported on "demand characteristics and full spectrum lighting effects on performance and mood" and was published on the Journal of Environmental Psychology in 1991 proving the interest on the quality of lighting (Jennifer Ann Veitch, Gifford, & Hine, 1991). A more recent paper on a similar argument is that one by Bellia et al. reporting on an example of an analysis in an educational environment (Bellia, Pedace, & Barbato, 2013).

From an institutional point of view, it is worth citing here two important and recent reports from the Scientific Committees of the European Union, where experts gave opinions on such a topic (SCHEER (Scientific Committee on Health Environmental and Emerging Risks), 2017). Those are:

- SCENIHR (Scientific Committee on Emerging and Newly Identified Health Risks), Health effects of artificial light, 19 March 2012
- SCHEER (Scientific Committee on Health, Environmental and Emerging Risks), Preliminary Opinion on Potential risks to human health of Light Emitting Diodes (LEDs), 6 July 2017.

Actually, the conclusions contain in both cases an observation regarding the fact that an improvement of the scientific knowledge is required to enable significant decision and regulations.

CoeLux capability of creating a realistic perception of an aperture on the daylight of course pass through the visual apparatus, finally coming to the brain. In contrast to some other technologies, it is worth noting here that CoeLux systems respect the entire list of perception cues (for example not discarding the binocular view) giving the realistic impression to whom is living the space lit by these.

In this perspective, CoeLux lighting possibly affects what is called Human Centric Lighting. Notably, studies performed until now in this field privileged focusing on three main factors when controlling the light, namely:

- spectrum of the radiation, mainly referring to CCT or color
- illuminance values, mainly measuring it as Vertical Illuminance
- exposure timing, setting administration of light with dynamical temporal profiles or considering dark periods

It is apparent also from the brief description given until now that CoeLux technology produce a multitude of effects not reducible to the cited factors. This is of course true also for daylight, and it is worth noting here that CoeLux technology presents some particular features exactly because it inherently uses the same physical principles of nature, those cited before.

It is worth noting that the unique light distribution CoeLux systems produce might affect also non-image-forming effects: as the simplest example one may cite possible effects related to the high brightness and directionality of the light source, combined with the presence of a diffused (blue) light. Notably, studies focusing on the impinging area of the retina have been performed (Glickman et al., 2003; Lasko, Kripke, & Elliot, 1999; Rüger, Gordijn, Beersma, de Vries, & Daan, 2005), but still it is missing a clear comprehension of the effects on the circadian system (Hanford & Figueiro, 2013). Then, there is room for studying in future the efficacy of light effects varying the direction of incidence as well as the spatial distribution. Noteworthy, as noticeable from the work done by the scientific community during last decades, those characteristics are pillars of daylight: beyond intensity and wavelengths, a huge effort of researchers that aim to characterize daylight focus on spatial characterization as well as on its variability, i.e. Sun movements or different weather conditions.

While one can note that real external condition effects can hardly be studied because of repeatability or noisy data, CoeLux may help in giving the occasion to study cited effects in a laboratory experiment. In fact, some studies already have been performed, as described here below, and the company is willing to proceed in scientific tests, demonstrating the great potential of this technology.

It is worth citing here the “Biophilic Hypotesis”, which reflects the importance of the contact with Nature in every moment of the day. The potential of CoeLux in terms of the effects on the Human Centric Lighting might also be described under such a perspective.

b) Impact on the lighting market

It is easy to understand that a significant number of lighting applications might be transformed by using CoeLux lighting (underground buildings, internal part of buildings, elevators…) and it is difficult to estimate the business impact. Also, an interesting indicator would be the Return Of Investment (ROI) because the considerable cost of CoeLux systems give, on the other hand, augmented advantages when using CoeLux lighting, for example considering the impact on health of building occupants (see below).

Last decades: a new, scientific, revolution

In a great review article, Schubert and Kim (Schubert & Kim, 2005) summarize the state of the art of lighting as well as the potentialities of LEDs, giving also a comparison with the legacy sources. "The high efficiency of solid-state sources already provides energy savings and environmental benefits in a number of applications. However, solid-state sources also offer controllability of their spectral power distribution, spatial distribution, color temperature, temporal modulation, and polarization properties. Such "smart" light sources can adjust to specific environments and requirements, a property that could result in tremendous benefits in lighting, automobiles, transportation, communication, imaging, agriculture, and medicine.”

For what concern non visual effects of lighting, a short citation from (Figueiro & Rea, 2016) is sufficient to recall the importance of such a theme: “Results show a significant increase in light exposure during summer. Sleep quantity and quality were also significantly higher in summer than in winter”. An introductory review is that from Edwards and Torcellini (Edwards & Torcellini, 2002), while a significant report in 2003 is that from LRC in the program “Capturing the Daylight Dividend” by U.S. Department of Energy and other authorities (P. R. Boyce, Hunter, & Howlett, 2003).

As written in the summary report of the Deeplite project, "CoeLux® also addresses the need for a more comfortable lighting overcoming the detrimental impact that the over-exposition to commercial artificial lighting has on human well-being. Up to today the lighting industry has mainly concentrated its efforts on the functional features of artificial lighting systems, while comfort and well-being effects have been neglected, thus leaving the above described problem unsolved. In todays' society, where one is often led to spend long hours in spaces, such as offices or other working contexts, blind to the natural light, the question of how lighting affects the quality of life is central. In such a context, CoeLux fill this open gap in the lighting market: providing a unique, unexpected view of a sunlit sky, comfortable on a psychological, emotional and biological level, in narrow spaces that allow for the sole presence of standard lighting fixtures."

On the market

A study regarding the state of the art reveals that there is not a clear shared strategy in which the huge competences and know-how reservoir might prosper and develop a new lighting. There are studies with not enough strong evidences, a lot of technologies of moderate innovation and an important role is played by customers' orientation to choice the lower initial cost. For example, it is worth reporting what is written in a sourcebook by the International Energy Agency:

"Algorithmic lighting offers lighting conditions varying in luminance distribution, light level and / or colour temperature over time. […] typically used to induce physiological responses, for example to increase alertness or concentration of pupils in schools or employees in office […] especially effective in windowless workplaces or workplaces with low daylight availability or for users with limited access to daylight, such as patients in a hospital and immobile elderly in a nursing home. […] Algorithmic lighting may produce a financial payback in terms of increased productivity or enhanced well-being but will likely also result in an increase in energy use". (Knoop et al., 2016)

On the other hand, today, several prototypes of virtual windows and skylights exist (IJsselsteijn et al., 2006; Kahn et al., 2008; Mangkuto, Aries, van Loenen, & Hensen, 2014). But, unfortunately, the research on the beneficial effects of these technologies has not revealed clear results (Kahn et al., 2008; Meerbeek & Seuntiens, 2014; Seuntiens, van Boven, & Sekulovski, 2012; Stokkermans, 2011; Wang, 2012).

The CoeLux technology entered the market few years ago and is going to play a significant role in this context.

The bright light source

Beyond theory and principles, the design of a new light source reveals some complexities even when functionalities are quite easy to mention. Before and during the design a thorough research and consideration work has to be conducted: there might be some compromises to be settled, technical problems to be solved and requirements to be taken into account coming from the productive and market purposes.

It should be noted that the real temporal sequence of the actions described here below has been different from the following exposition order. As an example, let us consider the certification, which of course was the last step: obviously, the comprehension of these tests started long before the creation of prototypes, in order to determine the correct development, starting from the choice of the emitter. In summary, I tried to put down in a written form a complex work, which involved together a plurality of different elements and competences, which were also mixed on a temporal basis.

1 - Lighting and technology

It is not a matter of this work to describe or discuss the giant field of lighting technologies and methods, nor the entirety of the CoeLux technology. On the other hand, the detailed design and the construction of the light source is strictly related to the working principles of the complete CoeLux system, as well as to the technologies of the lighting sector. Then, here below follows a recap of main elements which should be considered as a starting basis for this work. Secondly, there is a synthesis of the CoeLux technology, the real field where the source operates, from which a number of requirements descend, thus defining the contents of this work.

a) Lighting indoors

Studies on lighting design are various, comprising special applications (healthcare, stadium, shopping mall…), and the research is huge (for what regards circadian effect a reference is (Inanici, Brennan, & Clark, 2015)). An interesting recent paper includes different aspects of this work, and is worth citing here as an example of a possible approach for future studies (Khademagha, Aries, Rosemann, & van Loenen, 2016). Another recent paper reports: "The area-based circadian daylight metric described in this paper is applicable for informing decision-making in multiple contexts including all phases of the design process, as well as for assessing existing spaces" (Konis, 2017).

Artificial lighting

Obviously, lighting is a diffused practice; then, there is plenty of well-structured manuals, guidelines, text books, indications, also at a professionals level. Beyond the artistic design, the importance of which has been depicted above, scientific details and technicalities that refer to light can be easily found and formation courses hold regularly. Some references are here explicitly reported as this crucial theme will be not addressed in deep in this work; however, this is just a representative list and by far not complete. EN 12464 is the reference standard for public buildings for what concern indoor lighting, the Lighting Handbook from IESNA (Illuminating Engineering Society of North America) (Rea, 2000) and the one by SLL (Society of Light and Lighting) (P. R. Boyce & Raynham, 2009) are complete manuals, while two academic centers giving courses *ad hoc* are:

- Politecnico di Milano (http://www.polidesign.net/it/lighting)
- Lighting Research Center (http://www.lrc.rpi.edu/education/outreachEducation/index.asp)

One relevant theme, which is worth citing here, is the color rendition: this is based on a lot of parameters, the most important being the spectrum emitted by the light source(s). More than one "Colour rendering index" exist, even if the only one everywhere diffused is CRI-CIE1960UCS. Notably, it is widely accepted also the fact that it is not a good index (see for example (David, 2014; Houser, Wei, David, Krames, & Shen, 2013)). Similar procedures are those that refers to CRI-CIEDE2000 and CRI2012, but these, in fact, while improving reliability, do not produce results judged as universally acceptable. On the way there is more than one proposal: the most recent and interesting being TM-30, not yet widely accepted and lacking of some peculiarities. A large literature exists about this argument, which is not analyzed here.

Within the former standard DIN 5035-1 there was also a definition for a classification of color rendering levels. This definition is in practical use up to now:

1A	$R_a \geq 90$
1B	$80 \leq R_a < 90$
2A	$70 \leq R_a < 80$
2B	$60 \leq R_a < 70$
3	$40 \leq R_a < 60$
4	$20 \leq R_a < 40$

More precisely, DIN 5035-1 was replaced by DIN EN 12665 (Light and lighting - Basic terms and criteria for specifying lighting requirements) which does not contain anymore a definition of "colour rendering levels".

Passing by, it should be noted that for lighting design in retail applications, a typical requirement related to color rendering is given and in general $R_a > 80$ applies. However, as a more practical consideration, one should take into account that high quality projects typically require $R_a > 90$, especially for retail areas of soft goods (textiles) where a color rendering $R_a >> 90$ is suggested (level 1A, e.g. $R_a = 95$).

The present work somewhere reports CRI values, as these are the most diffused. However, it is worth to say here that these metrics refers to a uniform light source, whereas CoeLux technology intrinsically avoids this circumstance, creating at the same time the Sun and the Sky. The results reported below concern the light projector, and not the CoeLux product. Moreover, it is worth citing that results of index values using different metrics (i.e. also CRI-CIEDE2000 and other) did not differ a lot (in relative categorization) when measuring the source developed, giving good results in all cases (not reported).

These preliminary considerations and the just cited evaluation using different metrics were supported by Bartenbach GmbH contributions in the EU project.

Natural lighting

Considering the natural light, it is useful to describe its main characteristics from a lighting point of view. What is of pivotal interest are few data: the simple geometry (the sun disk and the sky dome) and the light quantities. For what concern the latter, it is sufficient to recall at least the order of magnitude of what is promptly available in the literature:

- Sun Luminance: 1.6 10^9 cd/m^2 at noon, decreasing to around 10^6 when at horizon
- Sky Luminance: 10^3 cd/m^2 in the brightest zones, and one tenth in the darkest

Spectra have been reported above; here below follow few Figures simply reporting some other interesting characteristics. The main point that is essential, however, is shown in the Figure showing the Colosseo in Rome under two different lighting conditions: while the cloudy day finally result in lighting with a (white) mixed light, in the clear day the peculiarity of daylight creates a unique condition that is apparent in the picture reported (Figure 9).

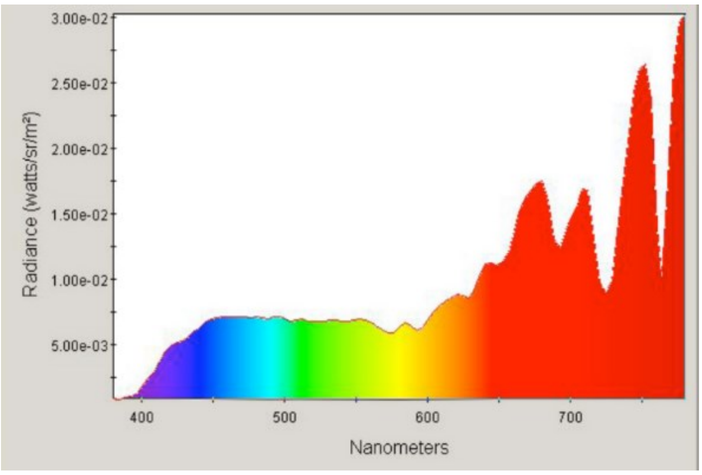


Figure 6 - Spectrum of the sunlight at sunset on a clear summer day

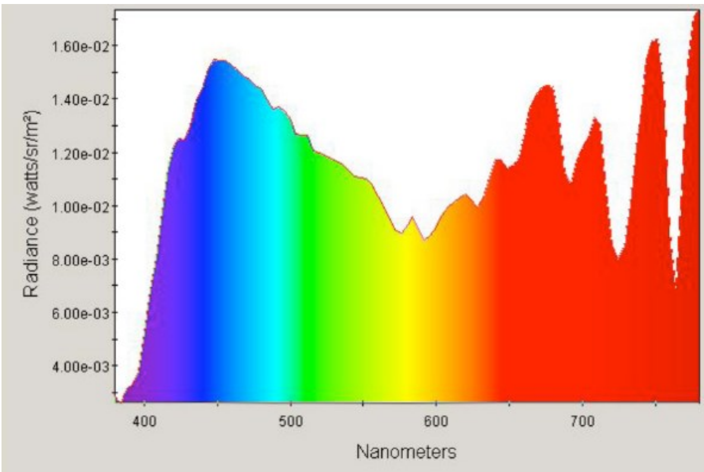


Figure 7 - Spectrum of the skylight + sun light at sunset on a clear summer day

For what concern Figure 6 and Figure 7, it should be mentioned that to obtain the shown data the same spectroradiometer was used by me as before for Figure 3. In these Figures, the Sun and Sky spectra at sunset are shown, isolating the direct component from the Sun (Figure 6) simply hiding the Sky from the target measured, or mixing both the light source's radiation, *i.e.* allowing both the Sun and The Sky illuminating the target (Figure 7). In Figure 8, a number of similar measurement are reported.

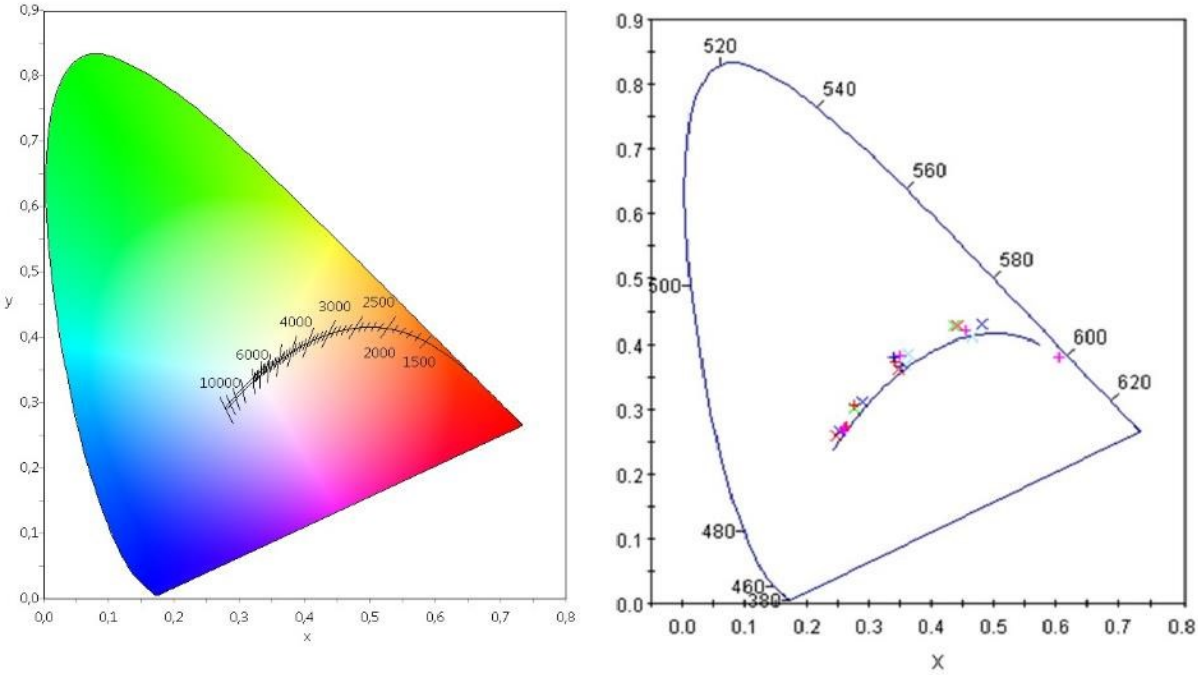


Figure 8 - A collection of measures of the natural light
showing the separate components and the mix of these (right).
The xy1931 color space is reported without additional data for reference (left),
showing also chromaticities of different ideal blackbody radiator (Planckian curve).

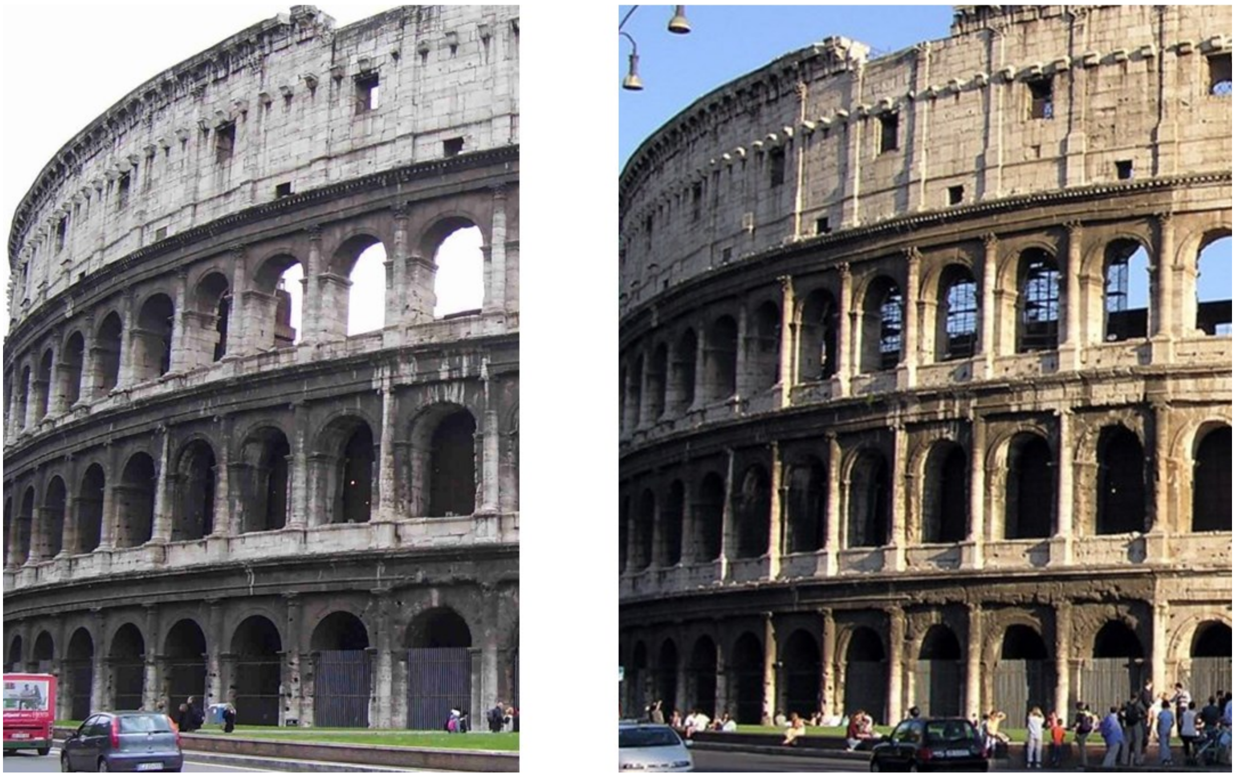


Figure 9 - Different lighting conditions on the Colosseo (pictures from the web, unknown authors)

In addition to what has been mentioned above, it is worth citing here, as a reference, the papers from the “Color Imaging Lab”, part of the University of Granada, which clearly analyze a multitude of aspects of this physical branch (Hernández-Andrés et al., 2003; Hernández-Andrés, Romero, & Lee, 2001; Hernández-Andrés, Romero, Nieves, & Lee, 2001; Peyvandi, Hernández-Andrés, Olmo, Nieves, & Romero, 2016).

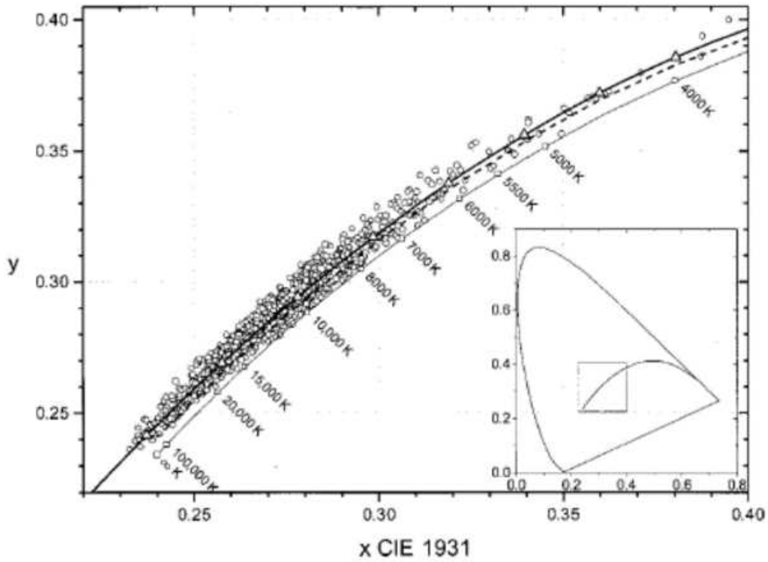


Figure 10 - Collection of daylight measures in Granada, from (Hernández-Andrés, Romero, & Lee, 2001)

Also, it should be considered that beyond the Rayleigh scattering other scattering phenomena occur which have an impact on the daylight. For example, Preetham, Shirley and Smits clearly explain that “The term haze refers to an atmosphere that scatters more than molecules alone, but less than fog. […] extra scattering is due to particles suspended in the molecular gas. These particles are typically much bigger than molecules” (Preetham et al., 1999). As explained by the Mie scattering (van de Hulst, 1957), these particles scatter light almost independently from the wavelength (at least for what concerns the visible radiation), then produce a white diffused light. Such diffused light for example causes the “bleaching” of the sky when the air is not clean.

Another field of study, which refers to similar aspects, is that one which accounts for a remarkable application: indoor natural lighting. This is a non-obvious discipline that should take into account a significant number of parameters; interesting documents are in particular those from CIE (for example (Darula & Kittler, 2002)), while a recent paper is (Mardaljevic & Roy, 2016). Of course there are data and different analysis available (see for example (Anselmo & Mardaljevic, 2013)), that treats deeply the argument, typically from a specific perspective, e.g. energy saving in building by means of optimization of daylight usage. It is not possible here to analyze all the links between these works, which are, however, interesting and numerous.

CoeLux lighting

It is worth listing here just few details of CoeLux lighting, which are reproduced in such a illumination, that stand as references that concretely drive the perception to "see" the natural light:

- Luminance balancing between sunlight and skylight
- Absolute chromaticity of sunlight and skylight and balancing between these
- Natural shadows with correct penumbras
- Light directionality
- Perception of an infinite distance
- Good spectral properties
- High brightness of the sun, visible also in the reflections

Figure 11 - CoeLux artificial window

Lighting effect given by CoeLux system is in fact a response to what is reported also in the summary of the CoeLux project: "The quality of artificial illumination is a major concern in developed and developing societies, where the structure of work areas, malls, community and sport centres, railway stations, airports, etc. forces a rapidly increasing fraction of the population to spend more and more of their time deprived of natural lighting. In many cases living space do not allow for the presence of windows or skylights, which would grant users the comfort deriving from visual contact with the external environment. When only artificial lighting is present, the space is felt as an isolated recess, disconnected from natural rhythms and unresponsive to the basic human demand of having a relationship to light which is more than just quantitative. The problem is particularly relevant for northern (or southern) regions, where natural illumination is lacking for a large part of the year".

A possible implementation may comprise some other details of the real Sun, for example the limb darkening effect, which refers to the fact that outer parts of the sun disk are in fact less bright that the center, as much as 50%, this being a noticeable effect (Mullan, 2009).

In addition, there are noticeable effects that were not commented before, like the brightening of the horizon and the circumsolar radiation, that are far from being peculiar or strange optical effects but were not treated in detail. Notably, these characteristics are as familiars as colors around us but are not strictly necessary in this work, and, as said above, possibly give a draft for future implementations (see for example (Buie, Monger, & Dey, 2003)).

b) Non visual effects of light

Above it has been cited the importance of the effects of light sources, which can have an impact on the society, and the three categories were exposed (Visual, Emotional and Biological impacts).

One might also refer to a different categorization: Visual and Non-Visual effects, the latter being a general expression that includes Emotional and Biological effects above cited. Another expression that is used by experts and it is similar to the latter is Non Image Forming (NIF) effects. It is worth noting here that IESNA uses "optical radiation" for the sake of clarity when referring to responses in humans other than the stimulation of the visual system.

Clear examples of what is happening with respect to these themes are, for example, the position statements by IES dated 2010 (IES Illuminating Engineering Society, 2010) and that one by CIE (CIE, 2015a).

Light impacts humans playing a major role in mechanisms which regulate stress, fatigue and, more generically, mood (Edwards & Torcellini, 2002). From a medical point of view, a recent, comprehensive, review of effects of blue light on the circadian system and eye physiology can be also found in (Tosini, Ferguson, & Tsubota, 2016).

Czeisler efficiently synthetized one of the effects: "Light impacts on our circadian rhythms more powerfully than any drug" (Czeisler, 2013)

Regarding the effects of light, a huge quantity of discoveries has taken place during last decades, both regarding the mechanisms that regulate these and the possible applications, for example, (Benedetti et al., 2003; Brainard, Hanifin, Rollag, et al., 2001; Brainard, Rollag, & Hanifin, 1997; Chellappa et al., 2011; Figueiro, Bullough, & Rea, 2003). From a scientific point of view, rod and cones have been described as a fundamental part of the eye during centuries, but only recently also the *intrinsically photosensitive Retinal Ganglion Cell* (ipRGC) effectively take the honor to be considered as the third typology of photoreceptor in our eyes (Berson, 2003; Graham & Wong, 1995).

Chronobiology is the discipline that specifically studies what exposed here above, in particular when related to cyclic behavior of life aspects (Hastings, 1998; Wetterberg, 1994); an interesting review is (Walsh, Atkinson, Corlett, & Lall, 2014).

Besides chronobiological effects, light also has an immediate effect on neural transmitters system. Especially the availability of monoamines like serotonin, which is also a key component in affective disorders and sleep regulation, is modulated by light (Lewy, Wehr, Goodwin, Newsome, & Markey, 1980).

While studied during the decades (see for example (Brainard et al., 1988; Remé, Wirz-Justice, & Terman, 1991)), a substantial change in studies of light effects on humans occurred starting with the new millennium.

The interconnections between ipRGCs (discovered in 1923 by Keeler and identified in 2002 by Hattar et al), circadian entrainment (a very interesting review about this is (Golombek & Rosenstein, 2010)) and light have had a step forward in 1991, and came to an interesting level in 2001.

During that year, two groups published the melatonin suppression spectrum (Brainard, Hanifin, Greeson, et al., 2001; Thapan, Arendt, & Skene, 2001). Immediately, and contemporary to LED mass adoption, the interest on such a theme grew (Rea, Figueiro, & Bullough, 2002).

The scientific community is still working on these aspects (Figueiro, 2014; Gnocchi & Bruscalupi, 2017) and the understanding of light effects is not yet complete (for example see (LedProfessional, 2016; Meyer et al., 2016)), moreover it can be supposed that a huge impact on human society may follow in future (e.g. impact on health) (Rea, Figueiro, Bierman, & Bullough, 2010).

In synthesis, light characteristics, which are critical factors for the regulation of our biological rhythm principally are: light intensity, spectrum and distribution, as well as current and previous light exposure time and duration (Bellia, Bisegna, & Spada, 2011; Lewy & Sack, 1989). A fundamental reference in this field is given by the "Report on the First International Workshop on Circadian and Neurophysiological Photometry, 2013", classified as Technical report CIE TN 003:2015 (CIE, 2015b), and the review paper by Lucas et al. (Lucas et al., 2014).

Methods used to study, characterize and analyze both the visual perception and the effects of light are various, most diffused being questionnaires, eye tracking, actigraphy, fMRI [9], EEG, ECG; notably, melatonin presence that is obtainable from biological samples is the best circadian marker in humans (see for example (Lockley et al., 2006)).

Without directly entering in the discussion of correct light administration protocols, sensitivity functions or possible time patterns (where a reference is, for example, (Lang, 2011), and it is of interest the publication by CIE (CIE, 2016)), it is worth noting here that the research about it is ongoing and that few are the certainties about it at the moment. Nonetheless, a relevant amount of studies consider a particular, limited, situation in terms of lighting condition and test sample (Bisegna, Burattini, Li Rosi, Blaso, & Fumagalli, 2015) also because of limited funding; however, the knowledge is increasing following a number of directions (Chellappa et al., 2014; Lieverse et al., 2011; te Kulve, Schlangen, Schellen, Frijns, & van Marken Lichtenbelt, 2017). Also, some aspects yet have not been tackled, for example in a recent paper an interesting question about the balancing between "too little daytime light, not just too much light at night" is considered (Figueiro, 2017).

Regulations are to come: for the moment there exist DIN SPEC 5031-100:2015 and DIN SPEC 67600:2013, the latter entitled: "Biologically Effective Illumination - Design Guidelines," that is quite explicit in its recommendations. The specification is also quite clear (and limited): "On the basis of current findings, it is recommended that humans spend about half an hour outdoors every day for the good of their health."

Circadian rhythms

Early research on circadian rhythms might be related to the names of Aschoff, Pittendrigh and Bunning (a more recent, but interesting paper (Aschoff, 1981)) who first scientifically investigated the relationship between organism and the light. During last decades it has been well established that lighting is important with respect to its non-visual effects on timing of circadian rhythms (Herzog, Takahashi, & Block, 1998). For example, it has been shown that exposure to bright light during the day and little light at night restores the sleep/wake cycle to a more stable state (Van Someren, Kessler, Mirmiran, & Swaab, 1997). Also, as Wehr, Aeschbach and Duncan report, when describing fundamental circadian physiological parameters it can be assumed "a model of the human circadian timing system in which two states, one diurnal and one nocturnal, alternate with one another, and in which transitions between the states are switch-like and are separately entrained to dawn and dusk" (Wehr,

[9] Vision produce a neuron response which can be studied, for example, thanks to fMRI. It has been observed, for example, that comfortable images produce a sparse neuron response while uncomfortable images produce a modest structured firing of neurons (Wilkins, 2016).

Aeschbach, & Duncan, 2001). Thus, there is recent interest in evaluations and calculations of circadian stimulus that the light actually drive (Amundadottir, Lockley, & Andersen, 2017; Rea & Figueiro, 2016).

Boyce wrote: "Initially, it was thought that the visual system and the circadian system could be treated separately (Boyce, 2006), but further studies have revealed that they are interconnected at a number of levels and that the impact of the intrinsically photosensitive retinal ganglion photoreceptor extends far beyond the circadian timing system (Boyce, 2011)" (P. R. Boyce, 2014).

The human internal clock is located in the suprachiasmatic nucleus (SCN) that is a group of cells found within the hypothalamus; this in fact constitute a biological clock that shows its own timing, providing the humans (and mammals in general) an endogenous regulation of the behavior. In fact, there exists a multitude of cyclical fluctuations in physiological, biochemical and behavioural aspects, circadian, infradian (e.g. following seasons) or ultradian (occurring more than once a day).

Also, molecular oscillators are studied by geneticists, and the presence of different genes is confirmed in both central clock as well as peripheral tissues (Gnocchi & Bruscalupi, 2017). Notably, the *2017 Nobel Prize in Physiology or Medicine* has been awarded to Jeffrey C. Hall, Michael Rosbash, and Michael W. Young for their discovery of "molecular mechanisms controlling the circadian rhythm".

Cited oscillators show proper period lengths that have not equal values, even so less these are equal to 24 hours. However, it has been proved that basic durations of a multitude of rhythms last in the range from 24.2 to 25.5 hours; experiments involved subjects that were deprived of any cue that might reveal the time of day (Moore-Ede, Sulzman, & Fuller, 1982). This is the main reason why the biological clock need a continuous adjustment, which is in effect a "simple" entrainment of oscillators; it should be noted that such an entrainment is really necessary, in order not to destabilize habits of the organism (Golombek & Rosenstein, 2010). The light is a powerful synchronizer of these periods; notably, light is the same factor that define the usable hours for activity (day/night), at least in ancient times; for sure it is not by chance that the human body (as well as other living systems) synchronizes oscillators paying attention to daylight!

It is worth noting here that rhythms might differ in function of other variables, for instance by age: an infant clearly show different periodical necessities and/or behavior from an adult, as well as elder people or kids. Requirements of different quantities or periodicity in fact occurs, caused by a multitude of factors that can not be easily summarized and exposed. Passing by, it should be noted that any treatment or simple exposure to light bounded by a protocol should be tailored also on additional details related to such a variable (aging). As an example, it can be cited the crystalline lens light absorption that increase with ageing and consequently change the circadian response to blue light, procuring a higher need of illuminance to obtain the same effect.

Also, there are evidences about the importance of "light history" affecting the impact of the same radiation on the same system (Chang, Scheer, Czeisler, & Aeschbach, 2013).

Moreover, the important role of chronotype should be mentioned: the synchronization of period with external cues is in fact not equal for everyone nor constant with respect to age, while is genetically determined (Turner & Mainster, 2008; Wirz-Justice, Benedetti, & Terman, 2013).

The cues that might resynchronize oscillators are in fact *Zeitgebers* (it is diffused to call such a time-giver with the German name after Aschoff (Aschoff, 1960)). Primary *zeitgebers* are in fact periodic variations of light and temperature; secondary *zeitgebers* might be our habits, such as meals; it is apparent that hunger and digestion work at best when naturally or methodically are set with some cyclic features; for example (Yetish et al., 2015). There is a variety of research about *zeitgebers,* and, in fact, a lot is not yet known. An interesting research branch (Pauers, Kuchenbecker, Neitz, & Neitz, 2012; Walmsley et al., 2015) considers also the role of color as a signal for entrainment, linking it to different natural CCT of dawn and dusk with respect to the daylight.

It is worth noting here that recent researches found direct links between the disruption of circadian rhythms and consequences on several diseases: sleep disturbances, cardiovascular disease, cancers incidence, obesity, diabetes, dementia... (Figueiro & White, 2013; Harb et al., 2015).

Physiology

As said before, one of the main *zeitgeber* is the exposure to the light; a consequence of what is described above is that lighting should be accounted for important (non-visual) effects on the human body and a wise control should be kept to allow for the correct entrainment of oscillators (Duffy & Czeisler, 2009; Foster & Hankins, 2007; Golombek & Rosenstein, 2010). However, it should be noted that the relationship between the central and peripheral clocks, and the multiple ways by which local and external cues affect them, is an active area of research open to new discoveries (Ibanez, 2017; Von Gall et al., 2005; Vriend & Reiter, 2015).

In a synthetic way, the mechanism is as following: in the retina, some receptors, the intrinsically photosensitive Retinal Ganglion Cells (ipRGCs, somewhere called also m-RGCs with reference to the melanopsin-expressing ability), are sensitive to light, as well as cone and rods, but do not contribute to vision and image forming. On the other hand, ipRGCs show a direct pathway that lead to the SCN, the so called retinohypothalamic tract.

So being, the SCN catches the information on daytime from the retina, allowing for the correct management of circadian rhythms. In particular, the pineal gland, found behind the hypothalamus in humans, receives information from the SCN and secretes the hormone melatonin in response to this message (see also Figure 12). The melatonin is the responsible of the regulation of the sleep/wake cycle. The neuroendocrine system is plenty of similar regulations and interaction between different mechanisms, whereas the results essentially affect the human health and wellbeing (Lucas et al., 2014).

Rather than being a simple process, the entirety of interactions is very complicated. It is well known that visible light, passing through S,M,L cones, produces signals which are processed before entering the optic nerve, actually combined into 3 channels; the first one encodes brightness, the remaining two encode color: a red-green channel and a yellow-blu channel. However, the interaction between ipRGCs, rods and cones is under study (Barrionuevo & Cao, 2016; Besenecker, Bullough, & Radetsky, 2016; Figueiro, Bierman, & Rea, 2008; Lall et al., 2010; Lucas, Lall, Allen, & Brown, 2012; Rea, Figueiro, Bullough, & Bierman, 2005).

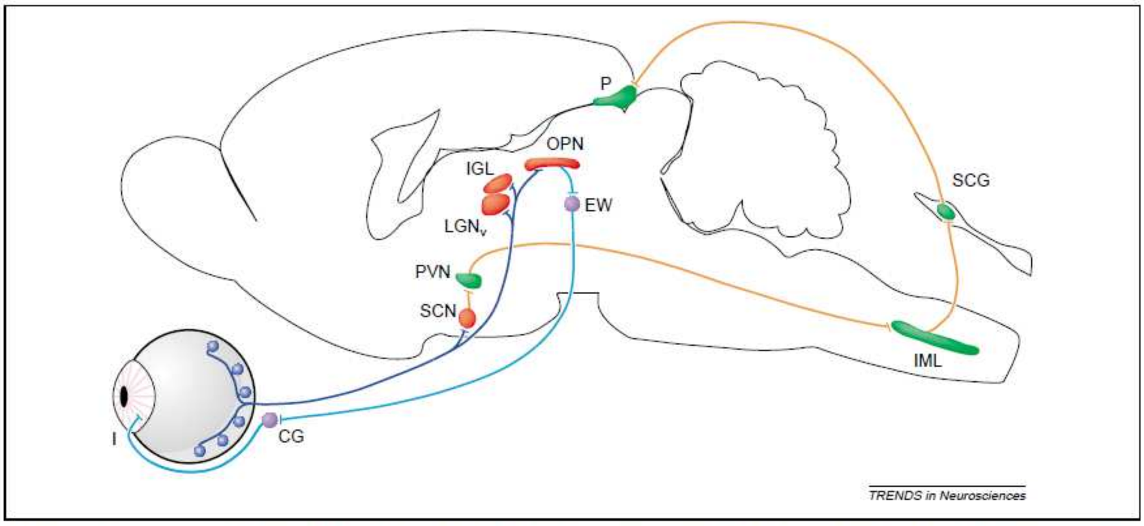


Fig. 2. Schematic summary of brain regions and circuits influenced by intrinsically photosensitive retinal ganglion cells (ipRGCs). The ipRGCs and their axons are shown in dark blue, their principal targets in red. Projections of ipRGCs to the suprachiasmatic nucleus (SCN) form the bulk of the retinohypothalamic tract and contribute to photic entrainment of the circadian clock. The orange pathway with green nuclei shows a polysynaptic circuit that originates in the SCN and photically regulates melatonin release by the pineal gland (P) through its sympathetic innervation. Synaptic links in this pathway include the paraventricular nucleus (PVN) of the hypothalamus, the intermediolateral nucleus (IML) of the spinal cord and the superior cervical ganglion (SCG). Another direct target of ipRGCs is the olivary pretectal nucleus (OPN), a crucial link in the circuit underlying the pupillary light reflex, shown in light blue (fibers) and purple (nuclei). Synapses in this parasympathetic circuit are found at the Edinger–Westphal nucleus (EW), the ciliary ganglion (CG) and the iris muscles (I). Other targets of ipRGCs include two components of the lateral geniculate nucleus of the thalamus, the ventral division (LGN$_v$) and the intergeniculate leaflet (IGL).

Figure 12 - Schematic view of light pathway (Berson, 2003)

A useful, and diffused, method to study such effects of light on humans is synthetically described in the abstract of (Pandi-Perumal et al., 2007) that is here reported: “The circadian rhythm of melatonin in saliva or plasma, or of the melatonin metabolite 6-sulphatoxymelatonin (aMT6S) in urine, is a defining feature of suprachiasmatic nucleus (SCN) function, the endogenous oscillatory pacemaker. A substantial number of studies have shown that, within this rhythmic profile, the onset of melatonin secretion under dim light conditions (the dim light melatonin onset or DLMO) is the single most accurate marker for assessing the circadian pacemaker. Additionally, melatonin onset has been used clinically to evaluate problems related to the onset or offset of sleep. DLMO is useful for determining whether an individual is entrained (synchronized) to a 24-h light/dark (LD) cycle or is in a free-running state. DLMO is also useful for assessing phase delays or advances of rhythms in entrained individuals. Additionally, it has become an important tool for psychiatric diagnosis, its use being recommended for phase typing in patients suffering from sleep and mood disorders. More recently, DLMO has also been used to assess the chronobiological features of seasonal affective disorder (SAD). DLMO marker is also useful for identifying optimal application times for therapies such as bright light or exogenous melatonin treatment".

Light therapy

Light being the major synchronizer of the biological clock it is interesting to consider also applications using this relation. There is a noticeable and growing interest in modulating light exposure in order to optimize effects on health and wellbeing, as a consequence of the found cause-and-effect relation between circadian rhythms disruption and some diseases. An important field of application is related to psychiatry (see for example (Van Someren et al., 1997; Wirz-Justice et al., 2005)), where light therapy is rather used with success; thus, one might refer to "chronotherapy" (Benedetti, Colombo, Barbini, Campori, & Smeraldi, 2001; Wirz-Justice, 2003; Wirz-Justice et al., 2013). In this field of research, unfortunately, physical parameters, and specifically light quantities, are not typically characterized (van Hoof et al., 2012), thus considerable differences can be found in the literature (Meesters, Dekker, Schlangen, Bos, & Ruiter, 2011).

c) Light sources

Light emission is an intriguing aspect of light-matter interaction; beyond the science, the technology developed to control this emission and to create lamps. Electrical lamps have been created since Davy's lucky day and Edison development: one gave the kick-off to the history of electrical light emission, using carbon as a starting material to create the arc, the second one in fact create the first reliable lamp. Since then, several kinds of lamps had been used, however, three are the most important classes, based on different light emitting phenomena.

1) Incandescent lamps make a filament glowing: electricity simply heats a small piece of metal and these become a light radiator, the basic phenomenon is the blackbody emission. In fact, the Sun also radiates according to this basilar physical law, and its surface temperature is about 5800 K. Unfortunately, lamp filament temperatures do

not reach this value; also, there are at least two well-known underperforming characteristics of this technology: lifetime, measured in hours, principally due to the consumption of the material itself (excluding the Sun), and efficiency (lm/W) because of infrared wavelengths radiated. Incandescent lamps can not be used in this work because of these two critical aspects, even if the Sun is incandescent and the story of commercial electric lighting starts from here.

2) Discharge lamps produce light by ionizing a gas, typically through electrons emission. While, basically, there are only two steps necessary for producing light with this technology, a huge variability of the characteristics exists, combining materials (comprising fluorescent materials), strategy for electrons production and electrodes technology, used vapors or lamp geometries. A significant effort has been done during decades obtaining interesting efficiencies and contained costs, as well as a significant light quality (where needed). Also, while maintaining the control on UV/IR rays emission, various lamp shape and dimensions can be ideated and, in fact, these sources reached a considerable diffusion in different fields of use. There are more than one example of such lamps that will be cited in this work, comprising Xenon lamps and Light Emitting Plasma. These are in fact very peculiar gas discharge lamps with interesting characteristics.
3) Solid state light sources have been developed quite recently, and actually entered the market in a significant manner only after the starting of the third millennium. Despite the relatively high costs of the substrate, of the doping procedure, and of the whole process, the diffusion of these sources increased hugely during the last years. Some advantages of this technology will be discussed later; the most remarkable characteristic is of course the high efficiency as highlighted also by the Nobel committee awarding in 2014 the invention of the blue LED. Moreover, it should be cited the fact that, with the main aim of reducing energy consumption, organizations as well as companies strongly encouraged solid state lighting. There are of course peculiarities of this technology: it is worth to cite here at least the fact that, differently from the other light sources cited in this list, the emitted light is strikingly monochromatic, this being sometimes an advantage, while for lighting is typically, as analyzed later, a disadvantage.

While this is a short summary, some technical points about these emitters will be found later in this work. For a complete dissertation of light sources, very useful publications are the “Lighting Handbook” both from IESNA and SLL (P. R. Boyce & Raynham, 2009; Rea, 2000).

It is interesting to note here that some technologies or strategies are not discussed neither in the cited books nor in the present work. The reasons are the following (and maybe other not written here): technical feasibility, costs, mechanical requirement for assembling, transportation conditions requested. During my work, I considered some of these at least from a theoretical point of view, but, at the end of the day, the scientific or technological effort required indicated also the practical solution, that is, to select doable strategies according to general lighting industry and market. Just to mention some of these cause of reflection: lasers, optical fibers, temporal or spatial multiplexing for increasing brightness…

d) The CoeLux technology

It is not possible to retrieve here nor the history neither the entire list of CoeLux characteristics; however, it is interesting to report some critical aspects synthetized in some public patent applications. It should be noted that a fundamental role is played by the nanostructured material (which constitutes the Rayleigh-diffusing panel), and by the design of the product itself, considering, for example the internal surfaces which in fact are a critical optical part.

In the patent US2014133125A1 (Di Trapani & Magatti, 2014) there is a significant description here reported.

The diffuser panel operates as a Rayleigh diffuser, i.e., as a panel which substantially does not absorb light in the visible range and which diffuses more efficiently the short-wavelength in respect to the long-wavelength components of the impinging light. The panel substantially does not absorb light in the visible range, and diffuses light rays of blue wavelength (450nm) approximately at least 1.4 times more efficiently than light rays of red wavelength (650 nm), where the diffusion efficiency is given by the ratio between the diffused light radiant power with respect to the impinging light radiant power.

Optical properties and microscopic characteristic of Rayleigh like diffusers are also described in detail in the patent application EP2304478 (Di Trapani & Pigazzini, 2014).

As for the perception, another description in (Di Trapani & Magatti, 2014) is relevant and reported here below.

It has been noted that the capability of an observer to evaluate the distances of objects, and, therefore the depth of field of the views that constitute a three-dimensional scene, is based on multiple physiological and psychological mechanisms. These are, for example, focusing, binocular convergence, binocular parallax, movement parallax, luminance, size, contrast and aerial perspective. Some mechanisms may gain significance compared to the others according to both the observing conditions (e.g., whether the observer is moving or still, watching with one or two eyes, etc.) as well as the characteristics of the scenery, these latter depending, for example, on whether objects with known size, distance, or luminance are present, serving as a reference to evaluate how distant the observed element of the scenery is. It has been further noticed that the natural quality of lighting improves whenever the maximum luminance of the light source is greater than approximately 10^6 cd/m^2. For those values, as a matter of fact, the light source generates enough glare for the source itself to be difficult to look at, thereby preventing the observer from evaluating the source's distance by means of the mechanism of eye focusing. Moreover, glare makes it difficult to detect possible non-uniformities in the luminance profile of the light source, thus making it difficult to detect differences between the image of the light source and an image of the sun.

The present lighting system allows for an observer to perceive the existence of an unlimited space beyond the diffused-light generator, similarly to what happens in nature when the sky and the sun illuminate a room through a window. Such a result is due to the presence of the dark box, which is coupled to the room by means of the diffused-light generator. The dark box allows for perceiving an homogeneous black background for every direction along which the diffuser panel is observed. Moreover, such an effect is improved by adopting a suitable observer-to-source distance.

With respect to the diffuser panel, i.e. the scattering center that reproduce the Rayleigh phenomenon above described, in the cited patent (Di Trapani & Pigazzini, 2014) the "device proposed" refers to the panel used in the CoeLux systems: an innovative type of artificial illumination capable of reproducing a fundamental and to date neglected aspect of natural illumination, that is, the simultaneous presence of two different light sources, namely skylight and sunlight, which differ in color, intensity, direction and spatial extension. In fact, the sky is responsible for the presence of a scattered light with blue as dominant component, i.e. “cold” in common terms, emitted from an extended surface and therefore capable of illuminating shadows. Instead, the sun is responsible for the presence of a light with a limited blue component, i.e. “warm”, which being emitted from an area subtending a limited solid angle, illuminates the objects only with direct light.

The phenomenon according to which the device proposed is capable of producing separation and different distribution between “cold” and “warm” components of the light produced by the source is the light scattering process in nanostructured transparent materials in “Rayleigh” regime, that is, in conditions in which the increase of scattering efficiency is inversely proportional to the fourth power of the wavelength. This phenomenon is the same one that determines, in nature, the color and luminosity of the sky, the color of shadows as areas illuminated by light coming from the sky, the color of direct sunlight after it has passed through the atmosphere.

Then, it is clear that the source object of this work is critically linked with all the technicalities reported here above, and that an effective design should take into account all these in order to produce, in combination with the same, a pleasant result.

2 - Specifying the sun

a) Preliminary requirements

The “optical design” of the natural lighting has been described above, and some technicalities have been introduced when referring to CoeLux technology; some concepts are particularly useful when discussing about the realization of a light source. In this chapter a short review of these is presented, along with considerations regarding the specific case treated. What is exposed here below is a summary I realized using the outputs of a number of discussion which involved also the EU projects partners. In particular, the team from the Insubria University (prof. Di Trapani and G. Gatti), the CoeLux Srl personnel (in particular D. Magatti) and the people from Bartenbach GmbH (W. Pohl and M. Laner).

Spectral and angular distribution: while the ideal solution would have been to reproduce an extremely bright source with full spectrum emission, an adjustable perfectly round emitting area, with a settable far field target (and, why not, also beam dimension and shape in some other plane perpendicular to the main ray), the first set of requirements is here below reported, along with the generating reasons.

- It is intended that the preferred light emitter is the LED, principally because of energy saving reasons. On the other hand, one of the critical characteristic of the same component is its brightness, as this should also reach a considerable value: a pale Sun is not the optimum situation one would seek out, and by no chance one can increase brightness by means of optics (because of the etandue conservation principle). In this chapter also other type of light emitter are cited, because at the starting point of this work was not clear whether there was the real possibility to obtain the result using the LED.
- The emitting area of the light source should be a round, “fully flashed” aperture. The latter condition means that no luminous structure should be perceived by an observer when looking at the Sun; as an example a picture is here below reported (Figure 13) where a round emitting area is strongly structured. In the same Figure two different sources are reported: on the left a safety grid is clearly visible as well as structures in the reflector. The source on the right is a high intensity discharge lamp, and the large dark spot in the center correspond to a capping structure, that creates a critical contrast.

Figure 13 - Appearance of two different bright stage lighting projectors (exposure times set to see structures)

- The required absolute diameter dimension descends from geometrical and perceptual consideration: the apparent dimension should be at least similar to the real Sun subtended angle, and the perceived distance definitely should be huge. Following from the latter and from the study of perception cues, the real distance between the source and the observer should overcame five meters. Considering the observer position with relation to the scattering panel (at minimum esteemed equal to fifty centimeters) the source should not be bigger than the width of a hand.
- The beam divergence should be appropriate to match an ideal rectangular target, namely an aperture where the panel is placed, equal to two meters by one with a tilting of forty-five degrees with respect to the main incident ray. From following considerations, it will get equal to thirty degrees by ten.
- The total flux produced should account for the sufficient lighting of at least a small sized room, that is, a total output of at least five kilolumen, where the overall efficiency play a significant role.
- The desired spectral composition of the emitted light has to be observed from different perspectives: firstly, it defines the overall color of the light in the ambient and the color rendition properties; secondly, it is the input of the scattering phenomenon that creates the radiation of the sky and that, once "filtered" appears as the sun beam. While the Rayleigh scattering is well reproduced in the CoeLux technology, it is difficult and not convenient to exactly reproduce the solar spectrum as an input. In fact, the cited effects can be controlled even by a rich and optimized spectrum using LED. Notably, the presence of these different factors (Rayleigh scattering and transmission function and the source spectrum) and the visual perception of the obtained colors should be finely combined to reproduce a realistic effect.

- The light distribution of the designed beam should finally be evaluated on a 4-meter distant screen, checking fine characteristics: a significant visible uniformity is needed, both in illuminance and in color distributions (it is well known that small variations could be easily seen in small structures, thus differences in light distribution could be accepted by the eye if occurring on large spatial scales). It is important also the minimization of aberrations inside the light beam. These become visible when projecting shadows, and have to be avoided.
- Thus, maximum illuminance and color variations across the entire spot (measured in the center and at the edge of the beam) should be contained in a 1:2 ratio and 200 K respectively.
- The illuminance on the target should be as near as possible to a flat-top distribution: strong decrement of the illuminance out of the target and low dispersed light (almost null) in the undesired directions are required.
- It is easy to mention some other requirements that follow from the fact that such a bright source should enter the market, namely:
    - Efficiency
    - Safety standards concerning electrical equipment
    - Electromagnetic standards
    - Photobiological standard
    - Reasonable operating conditions guaranteeing reliability (for mechanic, thermic and electrical stability)
    - Manufacturability

A preliminary evaluation of the geometrical and optical details follows here.

- The starting point is the definition of the light beam characteristics at the position of interest. The CoeLux system, in fact, is designed having an aperture (the window) with dimensions 2m x 1m: the overall divergence of the light exiting the source should account for these dimensions and, of course, for the distance between the source and the cited window. This distance is, in fact, a strict requirement given by the system. Moreover, the incidence angle of beam with respect to that window is 45°. Then, it is easy then to obtain, for these given input, the target divergence, which should be the following: 30x10 °, taking into account also the margins needed (Figure 14).
- The emitting area of the source should resemble the real angular dimension of the Sun as seen from the Earth (half a degree) or a least a similar value.
- Then, the quantity of light should be defined and, once the geometrical constraints are fixed, this will "simply" be a multiplying factor. It is worth noting here that the

technological evaluation has to be conducted, in order not to set unreachable requirements. It is important also to annotate that all the adjustable margins should be taken into account in order to optimize the design that comprise all the requirements.

- In fact, the easier way to obtain the expected luminance of the source is to use the given angular dimension of the emitting area: the subtended angle is equal to 2,4 10^{-4} sr when considering a "sun" seen under 1°. If the expected illuminance is equal to 2500 lx at the window level, descending from the photometric law (see Equation 3 and Equation 4) one can obtain that the luminance of the source should be around 10^7 cd/m^2.

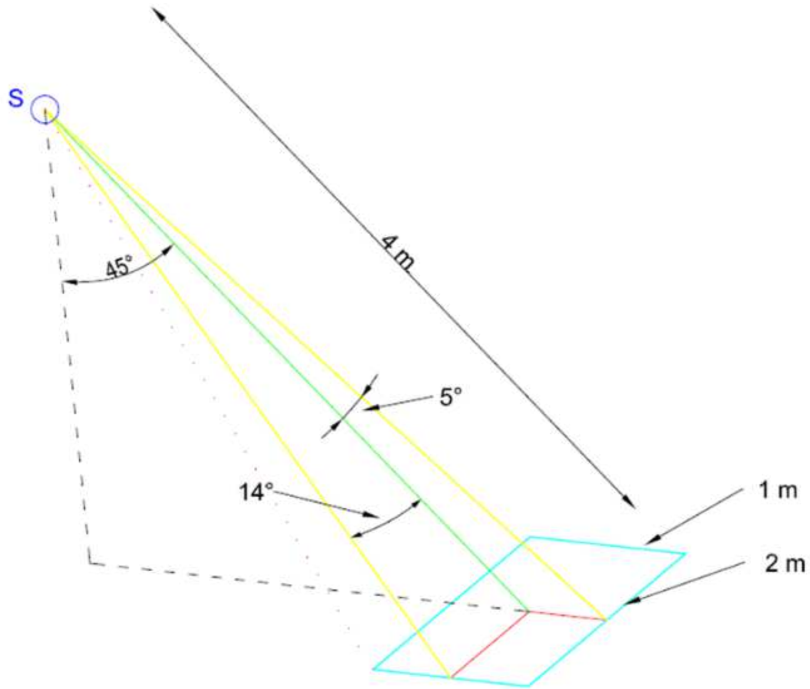


Figure 14 - Schematic view of the optical requirements

$$L = \frac{I}{A} = \frac{Ed^2}{A} = \frac{E}{\Omega_{app}}$$

Equation 3 - Luminance (L) calculation as a function of Illuminance (E) and apparent solid angle subtended by the source Ω_{app} . The intensity (I) is obtained by the photometric law and A is the emitting area

$$\Omega_{app}(2 * 0.5deg) = 2\pi(1 - cos(0.5deg)) = 2.39\ 10^{-4} sr$$

Equation 4 - Calculation of the subtended solid angle

A review of some figures of merit?

In addition to the above mentioned debate on color rendering indexes, it is interesting to report here a synthetic statement, which in fact mirrors a wider critic on CRI usefulness, born some years ago and already not settled.

"Color rendering is an imprecise construct associated with a light source, not with the objects being illuminated. Implicitly, and following P.J. Bouma's description of daylight as an ideal light source, a light source with good color rendering should make everyday objects in architectural applications appear vivid and natural, it should provide good color discrimination between subtle differences in hue, and should, from a marketing and sales perspective, be preferred as a light source over one with poor color rendering properties. Color rendering index (CRI) does not meet those expectations" (Rea & Freyssinier, 2010).

Thus, while specifying a light source, the best is to keep in mind that the spectral properties are a tricky detail, more than a number.

Moreover, numerous studies report critical observations regarding the adequacy of color perception, rendition and preference (depending also on cultural aspect) with respect to different situations or applications, as well as open deals on theory beyond these (Bodrogi, Lin, Xiao, Stojanovic, & Khanh, 2017; Islam et al., 2013; Lin et al., 2017; Whitehead, Papamichael, & Siminovitch, 2017).

At the same time, engineering aspects ask for a balanced compromise between requirements and the final effort to obtain the result, even more when planning the production, not to be stick to a particular desiderata; it is worth citing some of these aspects:

- CRI and efficiency
- Chromatic consistency and binning (thus, selection)
- Flickering quality[10] and power supply simplicity
- High luminance and low heat generation

b) Emitters and optics: an overview

Emitters: light producers

There are pros and cons of using LEDs as source. The high lifetime typical of this technology allows for designing durable architectural installations with no need for frequent maintenance, provided that the issue of thermal management of the source is properly addressed. Notably, LEDs are particularly appreciated also because of their spectral

[10] Passing by, it is worth mentioning that flicker of light intensity (that is not always related to the flicker of electrical power at plug level), as well as spatial frequencies in images actually cause non-natural working of the visual system, thus causing headache, for example.

characteristics being substantially harmless for the aging of sensitive materials in historical and artistic items.

The brightness usually comes at the expense of CRI, which is typically not excellent for LEDs. However, in principle there is the possibility of choosing between:

- high flux + high CCT + not excellent CRI for applications without peculiar CRI requirements, e.g. halls, passage areas, and similar
- acceptable flux + high CCT + high CRI for applications where colour rendering is essential, such as in retail and museum lighting

Other sources than LED, available on the market, actually achieve some of the characteristics required in the application which is the matter of this work, but some deficiencies appear, typically the performance in lifetime duration. It is worth noting that the particular class of short-arc lamps shows incredibly interesting features together, namely extremely high luminance and a rich spectrum similar to sunlight, the reason why these are used in particular applications, e.g. theatre; however, it is well known that the lifetime of such lamps is actually limited (Kon & Kusano, 2014).

In the following table principal characteristics of some lamps have been reported as well as apparent disadvantages of the same (keeping in mind that LEDs typically reach more than 20’000 hours of lifetime).

Manufacturer: BLV Type: HIT 150 6500K G12 	Electrical Power: 150W Luminous Flux: 11.000lm CCT: 6.500K Lifetime: 6.000h CRI: 80-89
Manufacturer: Osram Type: 4ArXS HSD 200 W/60 	Electrical Power: 200W Luminous Flux: 13.000lm CCT: 6.000K Lifetime: 2.000h CRI: ? (not specified) *UV-filter needed
Manufacturer: Osram Type: Baby SharXS HTI 250 W/D5/80 	Electrical Power: 250W Luminous Flux: 19.000lm CCT: 8.000K Lifetime: 3.000h CRI: >85

Table 1 - Some lamps with reported characteristics. Data from the EU project, collected by M. Laner

Also, a brief evaluation of Plasma lamps, with some experiments carried out by me with the support of CoeLux Srl, resulted in remarking that the chromatic behavior of such a technology is not stable as required in this project. It has been noted that measured spectra (basically in accordance with datasheet) of the tested Luxim STA 41-02 gave a chromatic emission distant from the blackbody locus (D_{uv} = + 0.007) which, as exposed below, does not match with the requirements, and variations during lifetime exceed requirements of indoor lighting. In fact, plasma lamps are finally adequate for external lighting where a high flux is needed. In Figure 15 is reported the emission spectrum taken from the LUXIM Datasheet "LEP STA Series - Light Emitting Plasma™ for high-illuminance applications".

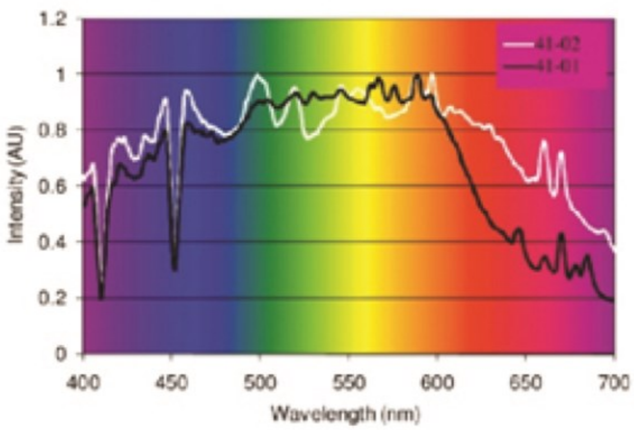


Figure 15 - Plasma lamp emission spectrum – LUXIM datasheet

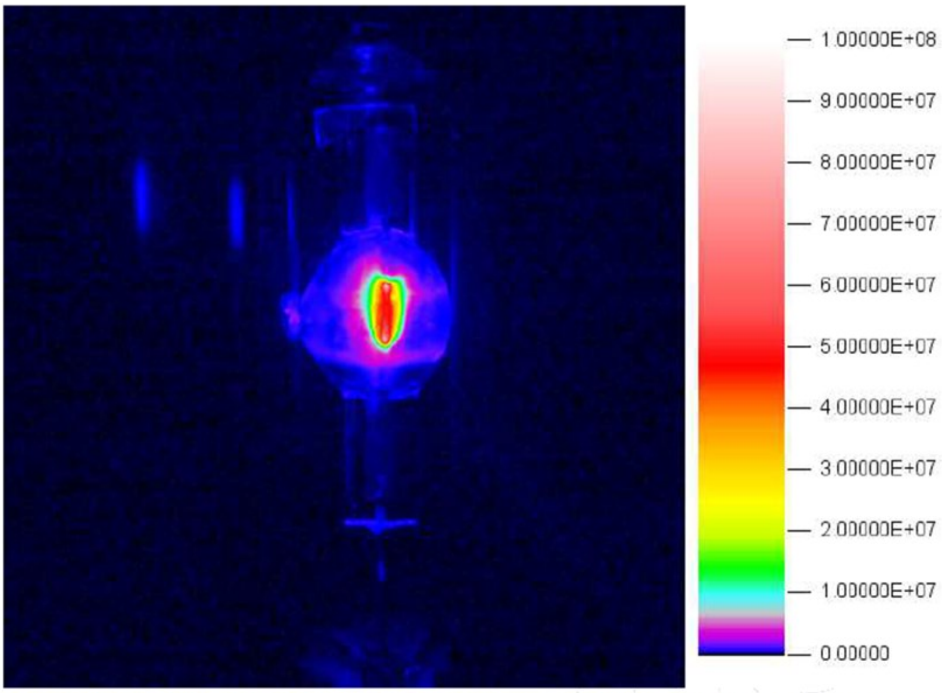
Despite showing a huge brightness, also Xenon lamps should be discarded as a possible solution for the sun projector. Here below main reasons supporting this conclusion are briefly reported:

- low luminous efficacy
- operating conditions not adequate to commercial lighting applications
- casing including safety glass (UV radiation: photobiological safety is critical) and special cooling systems
- predefined lamp positions

It is worth noting that, beyond lifetime, typically discharge lamps (including plasma lamps) also produce UV an IR rays, this being a detrimental characteristic, both because of additional components needed to block such rays (filters) and because of energy waste.

However, such lamps are useful in a lot of application: it should be noted that typically costs are contained with respect to the total amount of LED needed to obtain the same luminous flux, and that the punctual brightness may be very high, in some cases more than any LED available today.

On the other hand, the form factor is critical, as it should be noted that cited lamps typically need a considerable additional volume to work, because of mechanical parts (glass) where noble gases are contained, or needed dispositions of the electrodes. From the point of view of optics and size optimization it is a side-effect of serious importance.



BLV TOPSPOT HIT 150W 6500K G12: Luminance distribution (photo at Bartenbach GmbH)

Figure 16 - Metal halide lamp, luminance measurement (cd/m^2)

Notably, the coexistence of a huge brightness and a significant occupied volume per light emitter (Figure 16) could result in an acceptable mean luminance value which, as a matter of fact, might be acceptable for this work. However, the more the package is smaller, the higher is versatility, and the optics can be constructed *around* and *near* the emitter, allowing for a better optical design and control of light beam properties. At the end of the day, this is the reason why appearances of light sources like those in Figure 13 can not properly imitate a sun surface.

Then, the approach I followed has been to create a customized mix of small LEDs, working in order to fulfill all the requirements; thus, the final design has been defined accordingly to the optical features required. As apparent from following chapters, in this work the LED gave the possibility to design a modular optics with customized properties for each element, allowing for a uniform light output, which would have been impossible with discharge lamps. The disadvantage of such an approach is the need for multiple emitters, in terms of the Bill Of Materials.

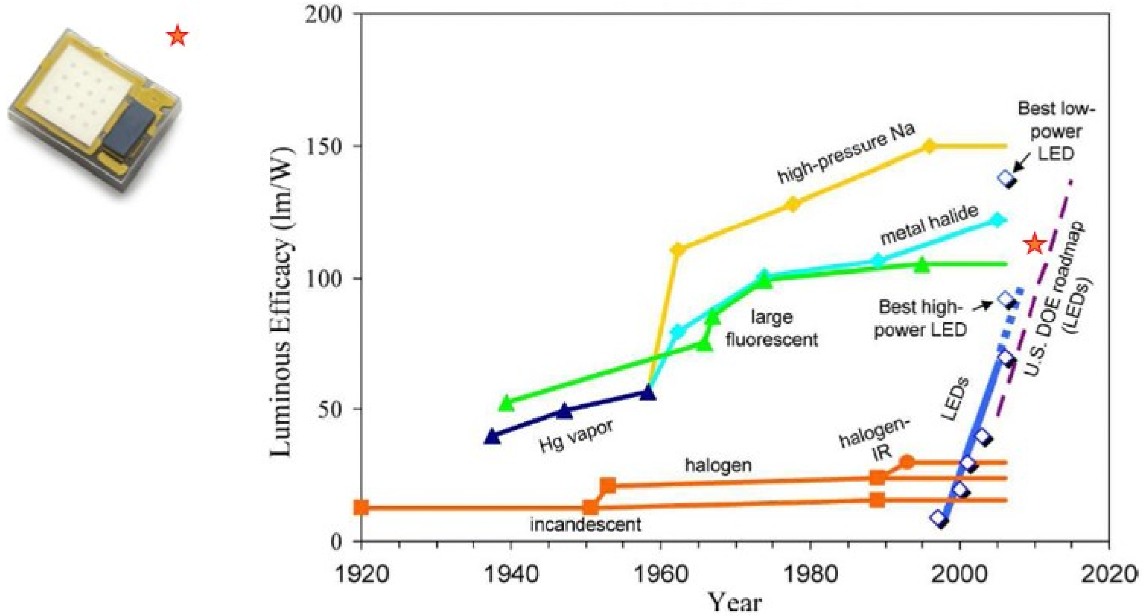


Figure 17 - Luminous efficacy of commercial white light sources by Krames, 2007. The blue curve indicate the performance of high-power LED. The dashed purple line indicate projections for white LEDs by the USA Department of Energy. The additional red star indicates the position in this graph of an exemplary LED source available form 2014.

Concluding this short overview regarding the emitters, it is worth noting that, independently from the used technology, one should always have a check on chromaticity of the selected emitter: both in term of stability and in term of consistency. In fact, the first one describe the behavior during the lifetime of the source, the second one the chromatic similarity between two sources as casually selected within a batch of production. It is easy to understand that a quality of a lighting product might critically depend on these characteristics. In our perspective it should be mentioned that the problem mainly rises in case of two product that are installed one nearby the other: both the sky and the sunbeam are expected to be similar, in principle. Moreover, a note should be written regarding the chromatic shifts that may happen because of temperature variations or during the switching of the emitter. From a technological point of view it is well known that the latter phenomenon is an hard-to-solve problem in metal halide lamps. On the other hand, thanks to the intrinsic characteristics of the LED (in particular the effective operation at different electrical), I succeeded in managing this problem as briefly described in the next chapter.

Optics

It is worth reporting here that in a brief survey carried out during the SkyCoat project, in collaboration with the Bartebach GmbH R&D team, about optical system of available projectors using Metal Halide lamps, some critical conclusion has been deduced as follows:

- projectors for metal-halide lamps with small radiation angles typically have at most 20% of the lamp flux within a solid angle where luminous intensity distribution (and thus also the illuminance distribution in the far field) declines by a factor of 3
- additionally there is no perfect cut off even if the direct radiation from the light source is shaded by cutters. When considering the radiation up to angles where the intensity goes down to 1/10 (which is assumed to be the "radiation angle") efficiency is typically not more than about 30% and the overall luminaire (entire radiation) efficiency is at most 44%
- without dramatically increasing the size of the projector these typical values cannot be significantly improved

In connection with what has been written before, it is here noted that LEDs are characterized by a more "direct" emission, typically showing a radiation pattern that is contained in a half of a sphere; moreover, the "dark" side is the natural mechanical and thermal support. In this perspective, is relatively easy to manage the LED emission: simpler optics comprehend both reflectors and lenses.

The most diffused optics in this sense are the Total Internal Reflection (TIR) lenses: (Figure 18) typically, such optical systems show good efficiency, and therefore should be considered for applications where LED technology and high efficiency are required.

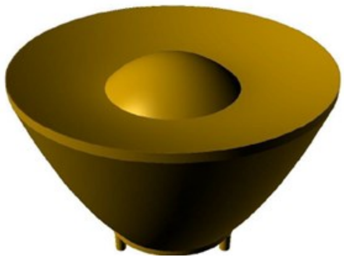


Figure 18 - 3D rendering of a common TIR lens for LED

On the other hand, these components typically present a rotational symmetry, not allowing for close packing, hence contributing to the creation of dark areas that can hardly be avoided in beam projection or when looking at the appearance of the projector. Moreover, due to the refractive mechanism involved in the TIR optical system, the issue of chromatic aberrations should be evaluated in order not to affect the projector's qualitative performance.

A significant parameter frequently used to characterize optical system is the value "cd/klm". Notably, such a quantity is an appreciable indicator of the intensity of the light that will exit the source once an emitter is positioned according to calculations. It is worth to mention that the form factor of the emitter is critically involved. Optics on the market often show this indicator as a parameter of interest.

In practice, every source/application requires a dedicated optical design if the constraints are strictly defined. It is not easy to categorize complex optics nor to explicit basilar working principle. The procedure followed for the development of the optical system used in this work is described below, where the continuous discussion with experts of lighting systems (Bartenbach GmbH) and components suppliers (companies producing optical parts) sustained my research work. In the framework of the EU projects, thus considering the required characteristics, I coordinated the work on the light projector described in the next chapters.

3 - Designing the sun

a) Matching requirements with components characteristics

LED

In this paragraph there is a short description of key factors encountered during the conduction of this research while working on LEDs aspects; there is plenty of literature reviewing the history of the LED as well as its potentialities and state of the art processes. Examples of this are two extraordinary paper reviews: “White light-emitting diodes: History, progress, and future” by J. Cho et al. and “Status and Future of High-Power Light-Emitting Diodes for Solid-State Lighting” by M. Krames (Cho, Park, Kim, & Schubert, 2017; Krames et al., 2007).

Excellent synthesis are also reported in two books: “Light-Emitting Diodes” by Schubert (Schubert, 2006), and “Handbook of Visual Display Technology”, in the chapter 6.4.1 written by Krames (Krames, 2012), which gives also an efficient description of the mode of operation. Also, from a theoretical point of view, it is of remarkable value the paper from Schubert et al. (Schubert, Kim, Luo, & Xi, 2006) as well as a milestone paper is the one from Nakamura and Krames (Nakamura & Krames, 2013). Finally, the paper by Dupuis and Krames, specifically address the high-brightness branch of LEDs (Dupuis & Krames, 2008).

Figure 19 - Timeline of Blue LED evolution as a function of the substrate

It is worth noting here that a significant work is ongoing in order to maximize quality, and in particular efficiency, following different strategies both in the industry and in the research community (Wright, 2015). An example can be the structuration of used materials (Chuang & Wuu, 2015) or the usage of quantum dots replacing phosphors for “the realization of quantum dot based white light-emitting diodes for general illumination” (Luo, Chen, Liu, Xu, & Wu, 2015; Shimizu et al., 2017).

While LED can really exhibit high efficiency values, this is not easily obtainable for every case: for example, an efficient LED emitting white light showing both high CCT and good color rendition properties has been a rarity until the year 2015. It should be noted that even today this combination is not required by the market and from this fact follows the lack of optimization of production processes and the fact that this kind of LED does not reach extreme efficiencies, as well as the scarce availability (or high costs) that are related to the procurement of the same. Unfortunately, this is exactly the case that would best perform in the source object of this work.

There are a lot of theoretical and technological reasons why this combination is an hard-to-reach target as analyzed, for example, by Chhajed et al.(Chhajed, Xi, Li, Gessmann, & Schubert, 2005).

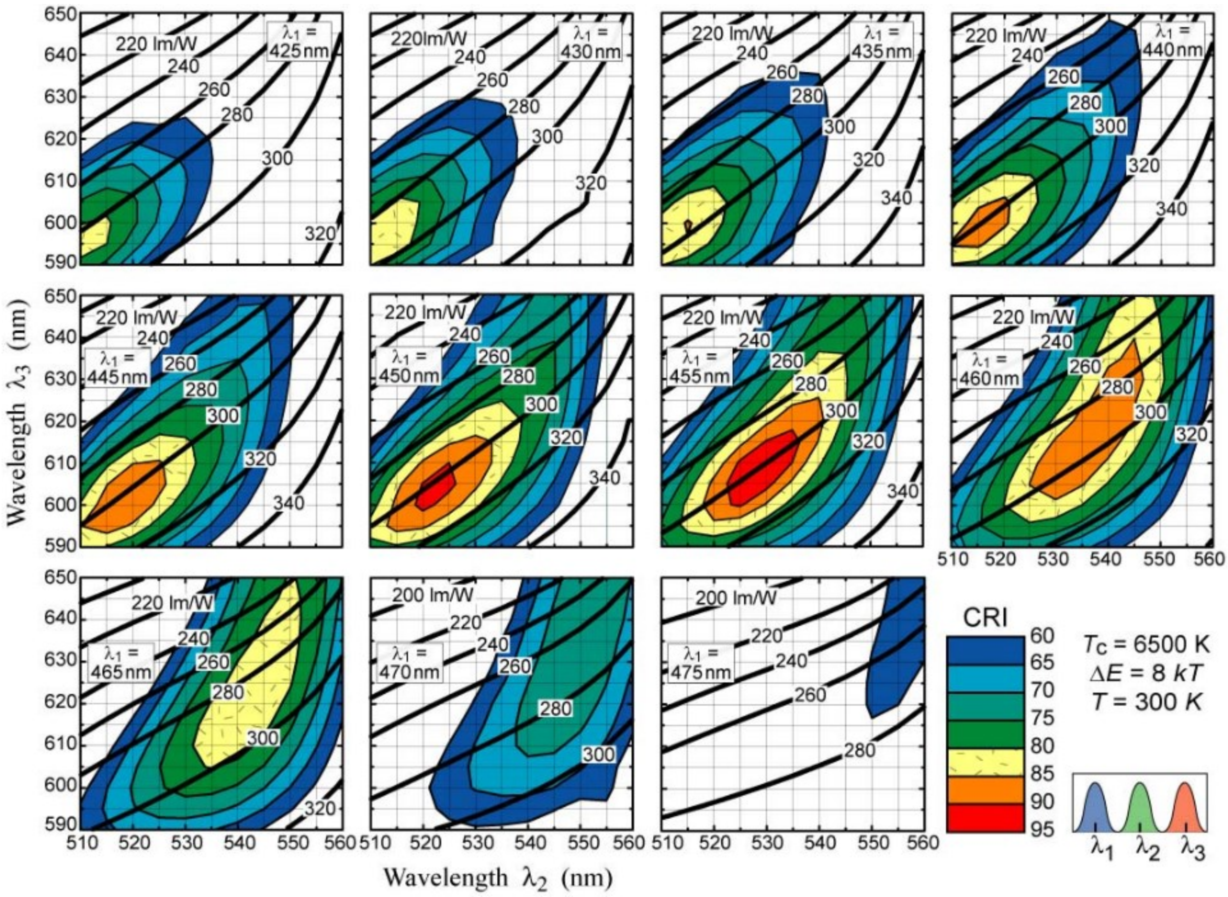


Figure 20 - Luminous efficacies of radiation (LER) and color rendering index (CRI) of different white trichromatic LED sources with correlated color temperature (CCT) equal to 6500 K, shown as a function of the three wavelengths (from Chhajed et al .2005)

Also, I have found a caustic analysis in (Lei, Xin, & Liu, 2014). As it is clear from the comparison of the two images reported (here Figure 21), the authors put in contrast the theoretical result given by the simulations and practical designs with the following consideration. "This gap comes from the low WPE of commercial LEDs, especially for green LEDs. Once this obstacle is overcome by technical advances, spectral assemblage will have more applications and become more attractive. Currently, the selection of discrete-wavelength LEDs available on the market is limited, so some of the LEDs required (but unavailable) for the spectral assemblage must be substituted by LEDs that emit a nearby wavelength".

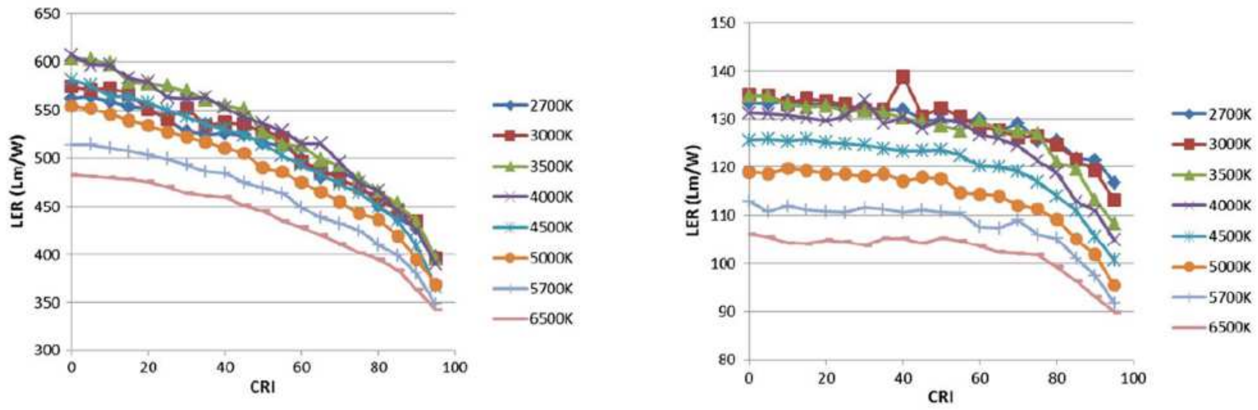


Figure 21 - Theoretical vs practical maximum LERs for each CRI at a certain CCT (from Lei et al. 2014)

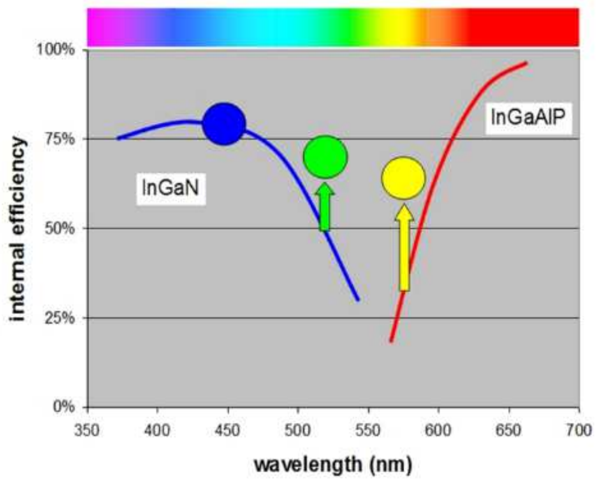


Figure 22 - Diagram of internal efficiencies of real LEDs

In Figure 22 the technological issue known as "the green gap" is shown: as a matter of facts, the efficiency for light production by an LED junction mainly resembles what is graphed. The development of processes might result in future in obtaining an improved efficiency also for green LEDs. This relates to what exposed above with reference to Figure 21, as the Internal efficiency is a relevant factor in the final WPE (Wall Plug Efficiency).

It is worth noting here that an additional requirements of CoeLux system that affect the light source starting from the emitter is the spatial uniformity (analyzed in detail later), as well as the extreme brightness needed, in fact these pose technical constraints which finally require a balancing between optimization of different factors.

As cited also before, one should deal with the well known problem of color consistency also with LEDs, mainly because of manufacturability reasons, as it is not straightforward to produce LEDs having the same characteristics, even maintaining the exact parameter during the production. In fact, LED manufacturers encounter huge difficulties in fabricating great numbers of devices with equal specifications. The solution applied is that at the end of a production line a process is implemented to subdivide products into smaller groups with similar performance parameters. This process, called "binning" and well known in the industry, is a typical example of the limits of the production with respect to the theoretical studies or research tests and is one of the main reasons for the high unit price of some LEDs.

It is worth noting here that a lot of research related to this theme has been done (Narendran et al., 2004; Vogels, Seuntiens, & Sekulovski, 2008), principally referring to the minimum visible differences; however, every project in fact should consider what are the acceptable differences in the product exploitation, matching these with the production requirements.

LED on the market

What is here below reported refers to the technology check mainly carried out during 2012-2013 and comprise solutions that were conceivable but have been discarded during the work. However, the highlighted characteristics exemplify the rationale that a technology check should follow at such a preliminary stage. Moreover, it is worth noting that the LED technology is continuously showing an impressive development, requiring for a frequent refresh of such a check. The realized prototypes took into account this study and used solutions linked with the rationale exposed, but in fact comprised also most recent developments available.

Generally speaking, a fast comparison between different types of LED actually gives an indication of typical luminance obtainable. In principle, one might assume that both the following classes are appropriate for this work: high power LEDs and Chip On Board (COB).

However, even a fast assessment can result in excluding a number of these LED. The reasons can be summarized as follows: the real average luminance of the component is affected by the design both of domed packages and of COB. In fact, these packages are valid because of other characteristics, comprising the efficiency (the dome, in fact, optimize the extraction of light) and customization, for example. Moreover, a COB component can be produced in huge quantities with a custom design with the need of a "small" investment, this allowing for special designs. In conclusion, however, the final values of desired luminance requested for this work can in fact be obtained just by a restricted class of LED, which are similar to those dedicated to projection applications. For a significant overview on high power LEDs, a useful reference is (Kückmann, 2006), while here below are reported some tables summarizing a part of the comparison made between different LEDs.

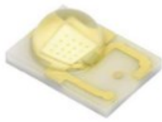
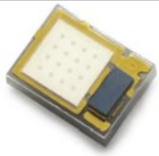
LED Osram Oslon CCT = 5878K Ra = 70,1 R9 = -27,9	
LED Luxeon Rebel CCT = 6424K Ra = 74,6 R9 = 0,8	
LED Luxeon Z CCT = 6327K Ra = 66,1 R9 = -35,3	

Table 2 Smallest LEDs on the market (2013).
This table has been compiled by M. Laner after shared discussion in the framework of the EU projects.

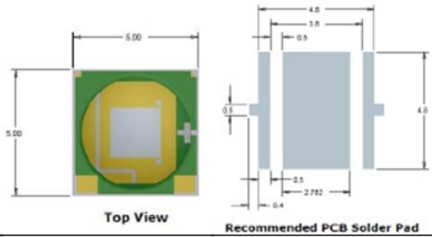
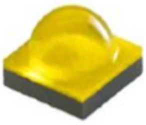
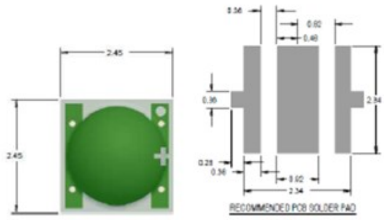
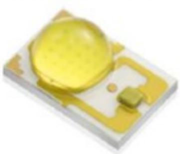
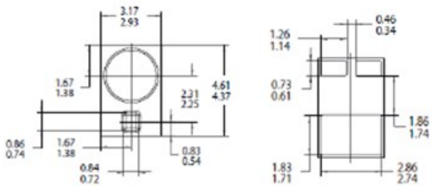
Name	*Selected characteristics*	*Dimensions and soldering pad*
Cree XM-L 	• 260lm – 280lm @ 700mA + 2,9V • 325% @ 3000mA, cold binned • Colour bin: ANSI 1 or more detailed according to [6] = 6000K to 6500K +/- 500K • CRI_{min} = 65	
Cree XB-D 	• New type since 11.01.2012 • 114lm – 130lm @ 350mA + 2,9V • 220% @ 1000mA, hot binned (252lm – 287lm) • Colour bin: ANSI 1 or more detailed according to = 6000K to 6500K +/- 500K • CRI_{min} = 70	
Luxeon Rebel ES 	• 310lm @ 1000mA + 3,1V • 130lm @ 350mA (binned on 700mA) • 230% @ 125mA, cold binned Colour bin: 6700K • CRI_{min} = 70 • Efficacy = 135lm/W (@ 350mA)	

Table 3 Some powerful LEDs on the market (2013).
This table has been compiled by M. Laner after shared discussion in the framework of the EU projects.

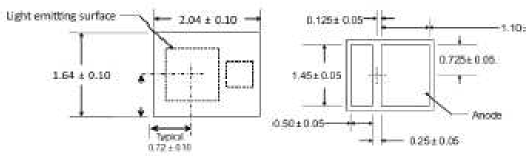
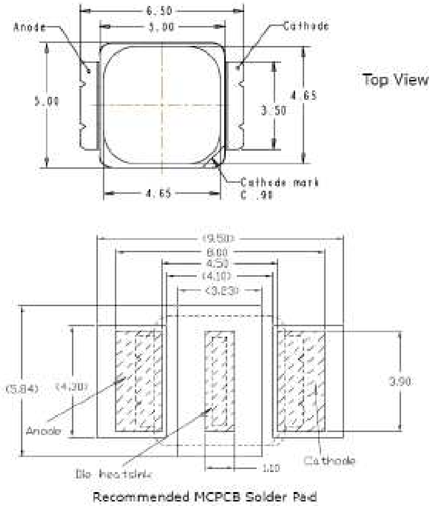
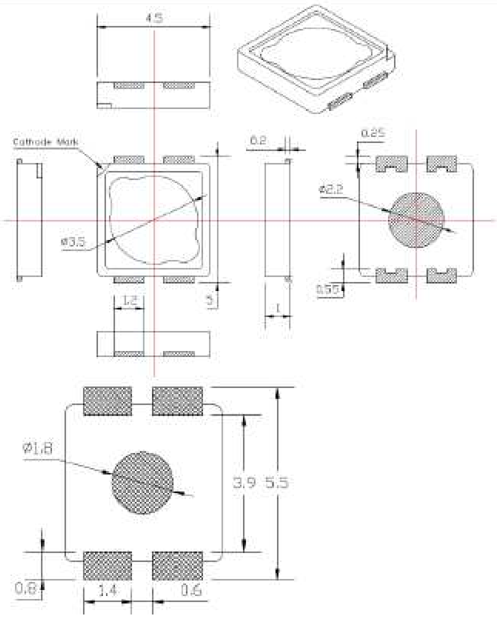
Name	*Selected characteristics*	*Dimensions and soldering pad*
Luxeon C 	• Φ = 95lm @ 350mA, 2,95V & 20°C (P = 1,03W) • CCT = 6500K available (e.g. colour bin: 1C or 1D = 6000K to 6500K +/- 500K) • CRI = 75	
Cree MX-6 	• 122lm @ 60mA, 20V • 225% @ 175mA • CCT = 6000K to 6500K +/- 500K) • CRI = 75	
Seoul P8 	• 100lm @ 300mA + 3,4V P=1W • 125% @ 400mA • CCT = 6000K • CRI = 80	

Table 4 Comparison of some LED characteristics.
This table has been compiled by M. Laner after shared discussion in the framework of the EU projects.

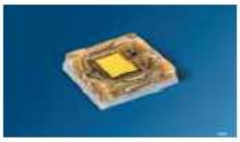
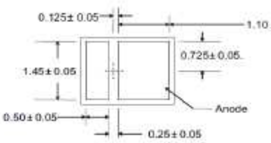
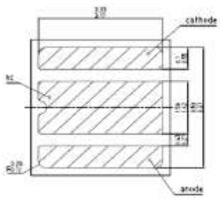
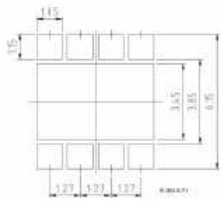
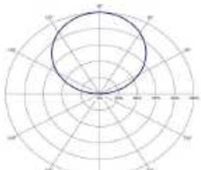
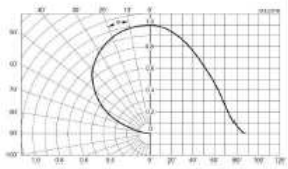
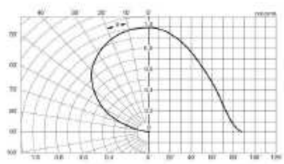
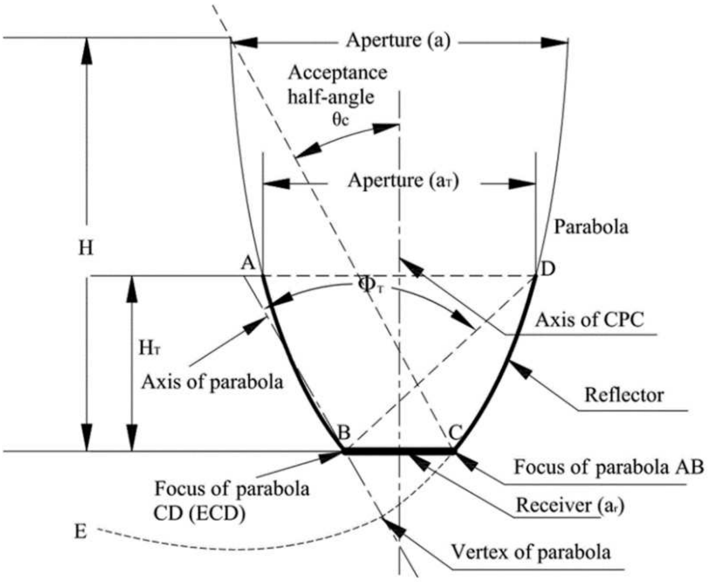
	Luxeon C	Ostar Compact	Ostar SMT
			
part. no.	LXCL-EYW4	LE UW Q9WP	LE UW S2W
price one piece [€]	1,30 €	8,44 €	20,18 €
price > 100 pieces [€]	<1,0€	<6,22€	<16,40€
typical flux @ 25°C [lm]	95	282	390
flux bin			NZ
typical electrical power	1,03	4,76	2,52 per chip = total: 10,08
electrical characteristics	350mA, 2,95V	1,4A, 3,4V	700mA, 3,6V per chip
max. costs [€/lm]	0,014	0,030	0,052
efficiency [lm/W]	92	59 @ 1,4A	50 @ 700mA according to datasheet
maximum flux [lm]	~ 110	~ 400	~ 450
@ maximum electrical power	500mA, 3,30V = 1,65W	3A, 3,9V = 11,7W	1A, 3,6V per chip = total: 14,4W
CCT [K]	in range of 5700 - 6500	x=0,31; y=0,32 = 6700K	6500
colour bin	2B+1C or 2A+1D	GM	
CRI	75		
lifetime [h]	20000		
dimensions	2,04 x 1,64 x 0,70 mm	4,00 x 3,75 x 1,40 mm	5,90 x 4,83 x 1,23 mm
soldering pad			
chipsize according to datasheet drawings	1,00 x 1,00 mm	1,30 x 1,65 mm	2,00 x 2,00 mm
flux density on chip [lm/mm²]	95	131,5	97,5
flux density on package [lm/mm²]	28,4	18,8	13,7
average luminance [cd/m²] calculation given data	30 Mio	41,8 Mio	31 Mio
average luminance [cd/m²] datasheet value			21 Mio
			
Disadvantages	- lifetime - CCT	- high costs - larger packages size - higher cooling effort	- high costs - large packages size

Table 5 Comparison of a first selection of LED candidates.
This table has been compiled by M. Laner after shared discussion in the framework of the EU projects.

Optics

A synthetic characterization of an optical system can make use of the *Etendue* calculations. In fact, this is a description of a recurrent principle in physics were the maximum concentration should be evaluated, for example widely used for optimization of photovoltaic systems (a similar optical description make use of the description of the Lagrange Invariant). As a general reference it is worth citing the book by Welford & Winston, "High collection non imaging optics", in particular Chapter 2 (Welford & Winston, 1989) even if superseded by another book cited later.

It is well known that one of the most efficient, and simplest, optical system addressing the concentration problem is the Compound Parabolic Concentrator for which is here also reported the Concentration ratio (Winston, Miñano, Benítez, Shatz, & Bortz, 2005).



$$C_{geo} = \frac{2a}{2a'} = \frac{1}{\sin\theta_c}$$

Figure 23 - CPC geometrical construction and maximum concentration ratio: primary aperture (a) over secondary aperture (a') [also called "receiver aperture" (a_r)]. Image from (Rao, Lee, & Hu, 2014)

These characteristics qualify the Compound Parabolic Concentrator as the ideal primary optics for high brightness design and, as described here below, the adopted solution make use of a certain arrangement of a multitude of these in combination with array of LEDs.

It should be noted that actually the CPC formula of concentration ratio describes the system as a concentrator in the perspective of energy per unit area. It follows that the acceptance angle define the input, and any direction of the light passing through the smaller aperture is accepted and considered. This point should be reconsidered when the purpose of the CPC is to create a light beam starting from the smaller aperture; however, also in this case there is a "concentration" increase, but it is in power density over the angles instead of power density over the area. The point is that, while the restricted beam (also called "acceptance angle" that is related to the larger aperture) is defined by the drawn geometry, the light exiting from the emitter, positioned in this case at the smaller aperture, do not equally fill angles: in the described case it creates a Lambertian emission, that follows the relation $I(\gamma) = I_0 \cos(\gamma)$. This observation do not have critical consequences on the design strategy, it is just a note on the correct way to consider the concentration ratio in case of using a CPC as collimator.

Describing the optical properties of CPC it is important also to note that the *Etendue* conservation is never achieved in real design. This statement is valid also for rotationally symmetric geometries: the design of a real CPC with circular apertures do not produce the *Etendue* conservation (Winston et al., 2005). In the perspective of having the highest possible luminance using LED sources, this point is even more critical in such that the form of the emitter is typically square. As considered before, LEDs with round packages are just a combination of smaller dices and the total brightness would be lower even at the starting stage.

However, the requirements of this project ask for a rectangular LID (Light Intensity Distribution) so the correct CPC should be rectangular by construction. In this case, the final *Etendue* will be higher because of inefficiencies of corners. It might be noted that, selecting some areas, the *Etendue* can be preserved in order to have the same luminance of the emitter also at the exiting surface, but it can be done at the cost of the total efficiency (see also a similar note on the Sun in the opening chapter), and it is not an applicable case of this work.

The Compound Parabolic Concentrator can be constructed also in a Total Internal Reflection version, using a dielectric material. The construction is similar but take into account the different refractive index of the material used (Winston et al., 2005).

The TIR version has been evaluated for this project, and such designs resulted in some pro and cons.

Advantages of TIR are:

- no coating process (and related problems)
- possibility of an injection molding out of one part (avoiding the assembling)

Some disadvantages emerge during an evaluation process: simulations gave an indication on "fully flashed" requirement fulfillment, as well as aberrations and possible stray rays: these factors were evaluated worst than the same in a hollow CPC. In fact, these are all related to the refractive nature of such components; however, these differences were evaluated as not really critical. Here (Figure 24) only the first of the cited differences is briefly shown, where the appearance of the two CPCs was under investigation (simulation with the Lighttools Design software). One hollow CPC and one TIR CPC providing the same angular light distribution were compared. In Figure 24 (right side) a sketch of the virtual setup is visible: two rectangular CPC (here a section is shown), were lit by an ideal light source fitting the entrance aperture. The image taken by a virtual camera collect quasi-parallel coming from the CPC, but reveals for both the different CPCs a structured apparent source because of the reflection inside the optics (left side of the image). However, as already noted, the preferable appearance is that one of the hollow CPC (it shows smaller structures and there are not the marked dark stripes as in the TIR CPC), but this difference is negligible. Such considerations as well as simulations were supported by the working team composed both by Insubria University people and CoeLux Srl personnel.

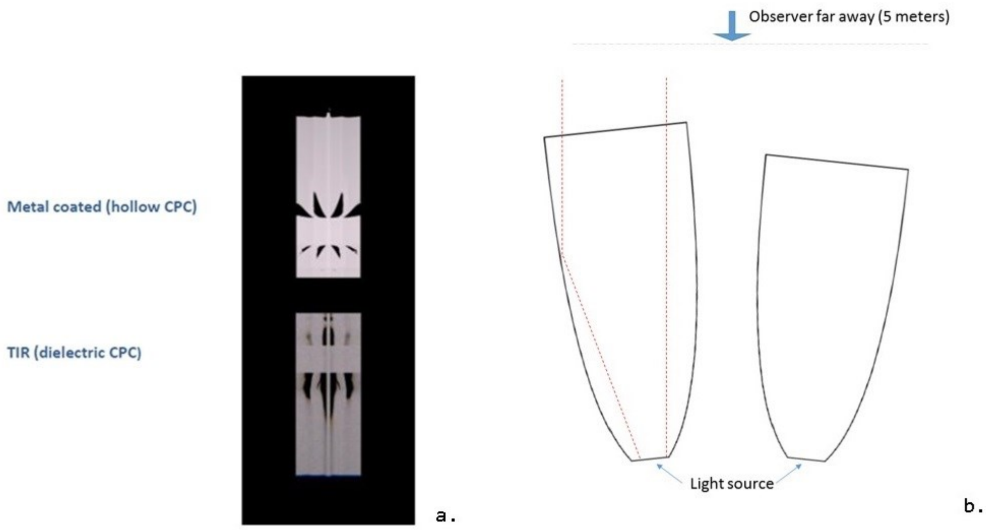


Figure 24 - CPC visual appearance comparison
(a.) the TIR CPC produces a darker structured image, (b.) schematic view of the simulation

On the other hand, pre-tests on heating were not positive, and plastic producers do not take responsibility on calculating the heating process. Moreover, the geometrical arrangement of the CPCs, designed for creating the round appearance is not an opportune disposition for molding.

Regarding the internal corners of the CPC: the curvature of the rectangle corners for the TIR CPC is not comparable to a metal assembling, in the sense that the latter show sharper edges, thus a more precise control on light deviation.

However, the most important factors were two: the junction between the CPCs and the efficiency.

The first one in fact, is a discontinuity that from an optical point of view is "active" in the sense that light might impinge in that point and be scattered everywhere; it is not easy to simulate the final effect, that depends on details related to the molds.

The worst characteristic is in fact efficiency: this is related to the fact that because of mechanical tolerances reasons and heating evaluations a small distance should be kept from the CPC and the emitting area. As apparent in the diagram in Figure 25, mechanical tolerances needed (0.5 mm) resulted in higher efficacy for hollow CPCs. According to numerical simulations, the collection of the light by a dielectric CPC (plane interface) is drastically affected by Fresnel's losses, and thinking about anti-reflection coating just on the smaller aperture of every CPC really does not make sense from a productive point of view. I was in charge of summarizing these characteristics while working on the specific task of the SkyCoat project.

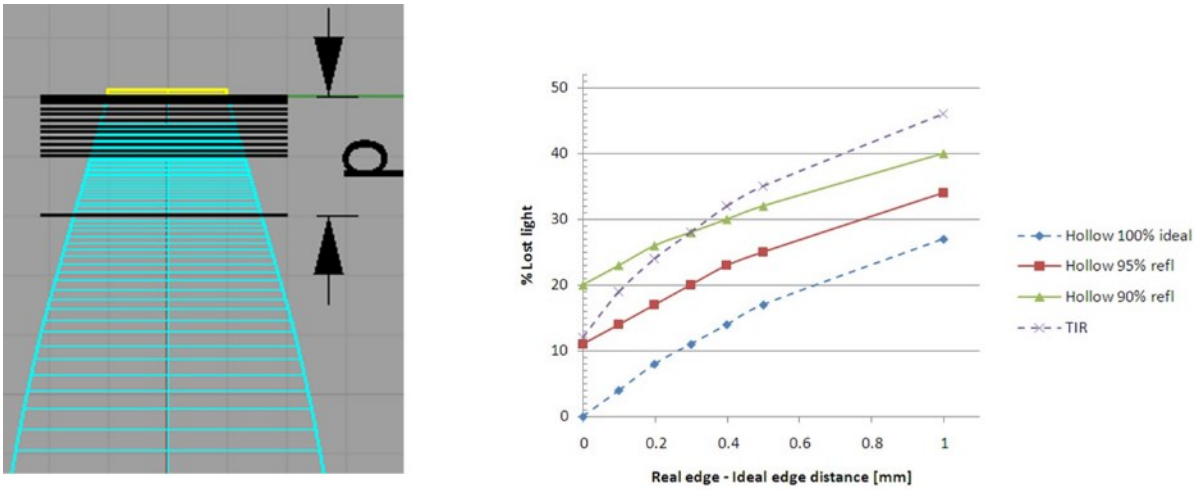


Figure 25 - Optical losses due to geometrical factors in a real emitter-optic coupling, reference is the ideal design with zero distance

It is worth noting here that different materials were considered for injection molding during evaluation; also those that are not frequently used for optics dedicated to general lighting (e.g. Silicone [not used in 2013 but now entering the market] or COC); however, none material succeeded in optimizing at the same time the two critical point cited before.

Evaluating the injection molding technique also for hollow CPC, a simple consideration is enough to close down such hypothesis: "The coating on the hollow CPC is not critical if we split it in two parts. Otherwise sputtering and vaporization are impossible (should we proceed with deep coating? low performances)" [private communication with a major producer of injection molded optics]. But, considering the splitting, assembling cost then would raise impressively.

b) Before developing

At this point of the work, it should be noted that in passing from preliminary spec to a commercial design, and even more so in passing to an industrial design, after introductory evaluation and before the design, when a huge effort might be required, it is worth to consider whether "collateral" requirements stand. As an example, a number of analysis have been made for this project, principally on expected efficiency and costs. In this part, some critical aspects are reported influencing the general design and a survey on the optical safety which took place.

As a first example, it is worth noting here that a top-quality design might request to have passive cooling, avoiding any fan, and, in this case, excluding parts in movement from this project. This, while being a good idea from an engineering point of view, is in fact a hard-to-reach target with a total power of more than 300W. More than one solutions have been explored, but all resulted in huge heatsink. In Figure 26 and Figure 27 a project involving heatpipes component is shown. I coordinated this project whereas the component design was specifically provided by a private company which has right competences in this field. In fact, given the result shown here below, this study was dismissed mainly because the significant occupied volume and previsions of costs.

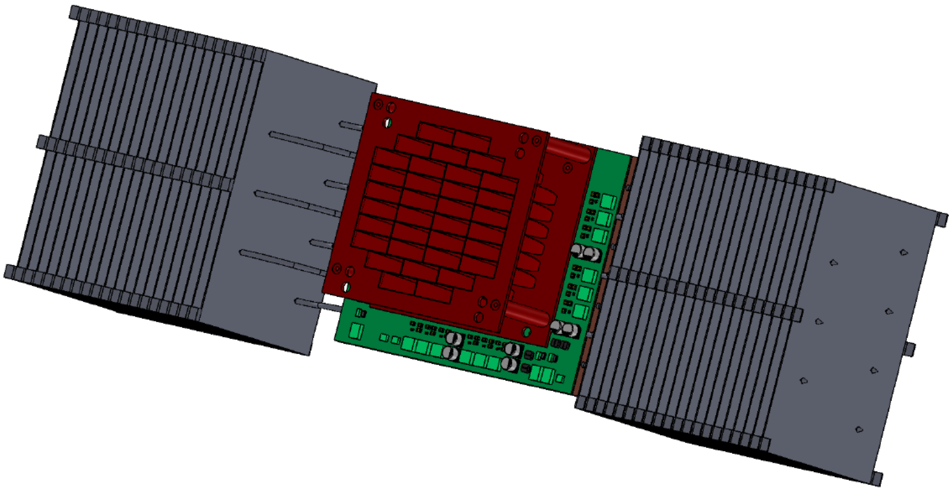


Figure 26 - Passive heatsink design 1/2 (the red and the green part are respectively the optics and electronics that will be exposed later, and are in fact the critical parts of the projector; in the next figure the optics module is indicated, this being the bigger part)

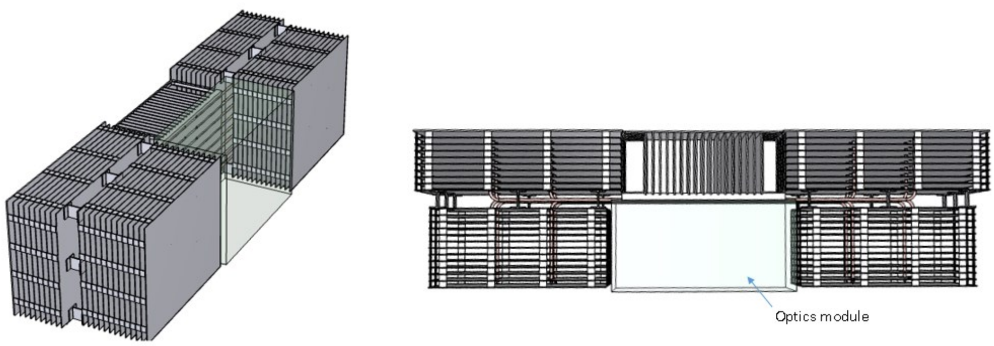


Figure 27 - Passive heatsink design 2/2

Obtaining colors with LEDs

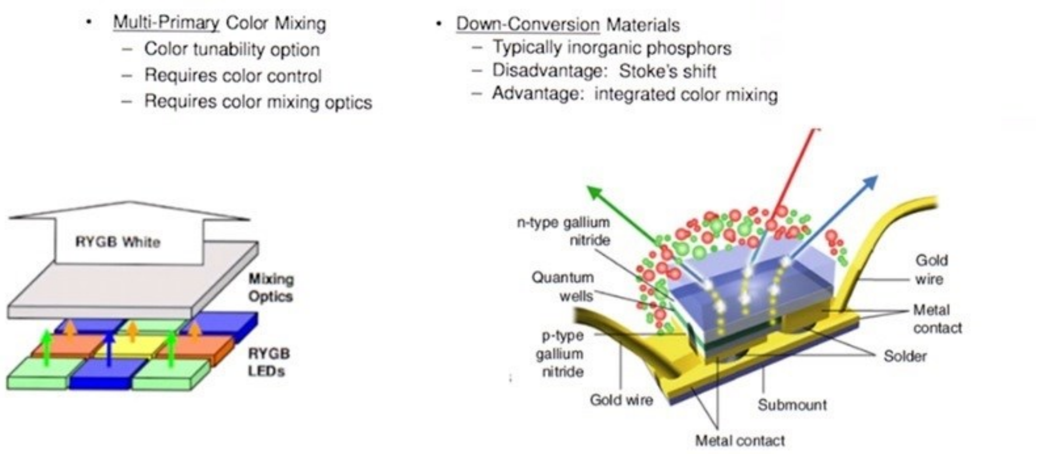


Figure 28 - Diagram of the two main different approaches to obtain a white emission from LED

Parameter/Light Source	RGB	White LED
Luminous Efficiency	High	Medium
Tunable	Yes	Usually restricted by manufacturer bins
Subjective Color Preference Rating [6]	High	Low
Skin tone rendition [6]	High	Medium
Light degradation	Comparable	Comparable
Control Electronics	Complex	Simple
Secondary Optics Design	Complex	Simple
CRI	High	Medium
Cost	High	Medium

Table 6 White light using LEDs: pros and cons of different solutions

The Table 6, reported from the Application Note AN58765 from Cypress semiconductor, summarizes and compares the most significant properties for the two different approaches.

In fact, there are criticalities in both columns, and a fine evaluation should be made in order to evaluate impact on product quality for all these.

It should be said that the optical mixing, the augmented complexity of the electrical design and the selection of bin are, in fact, a notable effort to take into account.

Moreover, with regard to the phosphors deposition, an additional observation might take place discriminating between different positions of the same with respect to the blue pump (e.g. remote phosphors, proximity phosphors, phosphors in the epoxy dome).

It is worth to note that Osram proposed, “a new, highly efficient concept for generating white light with a high color rendering index for general lighting applications” [Brilliant Mix – Professional White for General Lighting – Application Note] that works mixing a “special” white LED with and amber LED, obtaining very interesting properties. Unfortunately, this concept is not applicable in order to obtain whites with high correlated color temperature.

Notably, a different approach make use of violet radiation, also thanks to the bulk GaN substrates developed, in combination with three or more phosphors (see for example Soraa products).

Finally, it is worth citing also the multiplexing solution, even if a slightly more complex solution (Chaves et al., 2006; Murat et al., 2005).

LEDs criticalities

As written in a report by Lighting Research Center (Narendran et al., 2004), "most phosphor-based, unbinned, white LEDs show significant color variations”. With this condition, it is easy to understand why luminaire manufacturers were concerned about the application of LEDs, particularly when efficiency was not yet outstanding.

As reported by Narendran, at first the binning solution was deployed as following:

- 2-step MacAdam ellipse – For applications where the white LEDs are placed side-by-side and are directly visible
- 4-step MacAdam ellipse – For applications where the white LEDs are not directly visible

The points of interest in this work are slightly different because the source at the same time have the sequent characteristics:

- mix of multiple LEDs
- directly seen
- glaring
- casting shadows (and penumbras)

Moreover one should take into account also the possibility of multiple systems installed nearby.

Photobiological Risks

An evaluation of Photobiological Risks related to the light source emission, should consider the standard IEC 62471:2006 that assigns a Risk Group to the emitter according to the measured radiation. Basically, the applicable category is GLS (General Lighting Service) and warning labels should be applied according to the Risk Group obtained from the evaluation (if necessary).

These tests result in an assignment of a Risk Group:

- Exempt group: No photobiological hazard according to standard.
- Risk Group 1 (Low-Risk): Normal behavioral limitations on exposure prevent hazard.
- Risk Group 2 (Moderate-Risk): Hazard is precluded due to aversion response to very bright light sources or due to thermal discomfort.
- Risk Group 3 (High-Risk): Hazard even for momentary or brief exposure.

High-Risk luminaires (Risk Group 3) cannot be used in general lighting.

When testing an LED-based light source, it is apparent that no risk is expected coming from the UV or IR radiation, as the source does not emit such wavelengths. Hence, the spectral band that may give relevant results is that one relative to BLH (Blue Light Hazard). However, considering that the typical evaluation point is that one where 500 lx are measured, it descends that white sources may be hazardous only where the CCT is higher than 10000 K. A more precise and detailed description can be found in the "LightingEurope guide on photobiological safety in general lighting products for use in working places" (LIGHTINGEUROPE, 2013). Moreover, it should be noted that the source here described is expected to be observed in conditions where the illuminance is higher than 500 lx, then a complete assessment should take into account also the complete directives and users shall be advised by the producer about possible hazard (if any).

These simple considerations just give a first indication, the exact evaluation should of course be performed taking into account the final project and, once available prototypes or pre-production samples, by means of real measurements.

I was in charge of coordinating also this specific task of preliminary evaluation of the expected photobiological risk. I should mention that what is reported here below is the result which was obtained independently by Bartenbach GmbH R&D team and by me. We both conducted independent surveys and calculation also to obtain a well established result. Moreover, different accredited laboratories were contacted in order to obtain a dedicated support to go in a deeper comprehension of the argument (e.g. Underwriter Laboratories, UL Inc.)

A preliminary calculation shall take into account targeted parameters and deduce an assessment. Here below such a procedure is reported as implemented in the course of this research work, based on a spectrum calculated which is as much as possible similar to what is expected. Then, the relevant radiometric values will be converted to photometric values, considering this spectrum.

As the solid angle of the virtual sun in a prototype exceeded a field of view of 0.011 rad (i.e. a cone with an angle of 2 x 0.315°) the "Retinal blue light hazard exposure limit" according to CIE S 009, 4.3.3 has to be applied.

For what concern the blue light hazard, a convenient weighting function is defined in EN62471. Then, for the spectrum used, holds the following relation (where the weighting function is not shown, unit angle and unit area are simplified, lumens refers to the entire visible band and Watts are expressed with reference to the relevant blue radiation):

$$\frac{L}{L_b} = 2068 \, \frac{lm}{W}$$

Equation 5

For Exempt Group the luminaire need not pose a retinal blue-light hazard within 10000 s (about 2.8 h). For this long period of viewing, the procedure requires for an evaluation of the pertinent blue light weighted radiance L_B averaging over 0.1 rad (2 x 2.865°, see CIE S 009, Table 5.5). The fixed limit is $L_B \leq 100$ W/(m^2 sr) according to CIE S 009, (4.5b).

It results then that the equivalent luminance limit for the spectrum under investigation is L< 206800 cd/m^2. On the other hand, it should be noted that 0.1 rad exceed the angular dimension of the targeted artificial sun. Then, a significant evaluation can be done referring to the illuminance, referring to the equivalence reported in the following. The underlying reason will be clear at the end of the paragraph.

In fact, considering the simple system comprising a single light source, which shows a uniform luminance over the entire area for the considered angle of observation, the following equivalences holds:

$$L = \frac{I}{A} = \frac{Ed^2}{A} = \frac{E}{\Omega_{app}}$$

Equation 6

Where L is the luminance, I the intensity, A the emitting area, d the distance between the source and the point of measurement and Ω_{app} the subtended solid angle by the source from the observing position of the point of measurement (units have been dropped for the sake of clarity). The solid angle can be simply calculated from the definition:

$$\Omega_{app}(0.1 \;\; rad) = 2\pi(1 - cos(0.05rad)) = 0.007852 \;\; sr$$

Equation 7

Then, a numerical relation between luminance and illuminance for this case can be established, where values are expressed in candelas per square meter and lux respectively.

$$L = 127.4\ E$$

Equation 8

Notably, as the average luminance over a certain angle is requested, this equation is valid until the light source does not exceed the same angle (as in this case), and in the case the source occupy a smaller solid angle than the field of view considered, its luminance might also exceed this value. The point is that, for such a spectrum considered, the request for the blue radiation to respect the limit of $L_B \leq 100$ W/(m^2 sr) thus results in an even clearer request as the following Equation 9

$$E \leqslant 1623\ lx$$

Equation 9 – Limit for RG0 for the calculated spectrum

For Risk Group 1 (Low-Risk) the luminaire need not pose a retinal blue-light hazard within 100 s. For 100 s exposure duration the field of view for averaging L_B is 0.011 rad (2x 0.315°, see CIE S 009, Table 5.5) and $L_B < 10000$ W/(m^2 sr) according to CIE S 009,(4.5a). As the sun spot is larger than this field of view this implies a limit on the luminance averaged, calculated using above conversion, expressed in Equation 10:

$$L < 20.68\ 10^6\ \frac{cd}{m^2}$$

Equation 10 – Limit for RG1 for the calculated spectrum

Before the development this results were obtained by calculations.

It is worth noting that during the development another assessment took place using measurements referring to the preliminary prototypes. Then, the final measurement was conducted on the final prototype. What is relevant for this argument is just the spectrum, and relatively small differences occur between the results obtained with the calculated spectrum, with the preliminary spectrum and with the definitive measurements. In Figure 29 the result obtained for the preliminary spectrum is shown graphically.

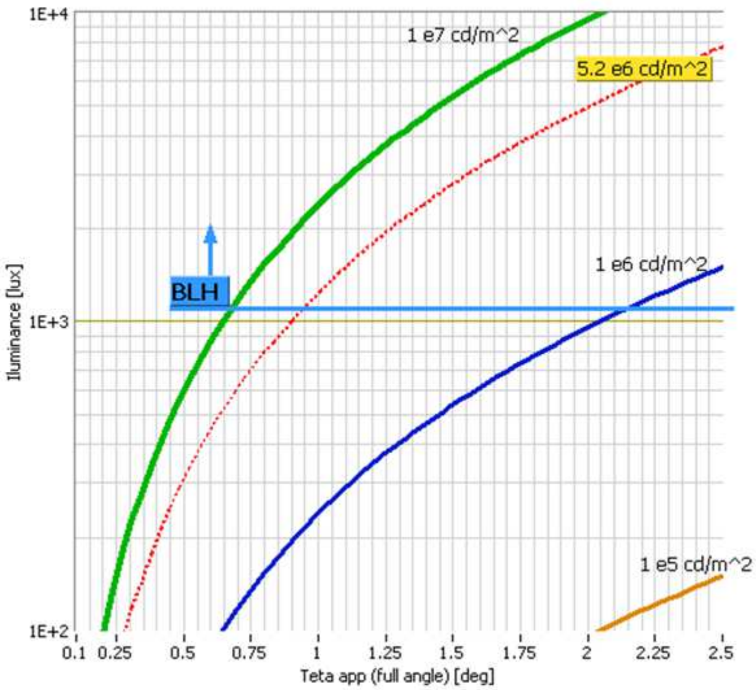


Figure 29 - Illuminance given by a source as a function of apparent dimension and source Luminance (refer also to Equation 6).
Blue Light Hazard limit for RG0 for the spectrum of the preliminary prototype is shown, and measured Luminance of the same is highlighted. For this spectrum, the RG1 limit was equal to 15 10^6 cd/m^2

c) Summary and definition of requirements

Once more is interesting to cite the patent application (Di Trapani & Magatti, 2014) where is also reported the concept of the light source that is significant for this work.

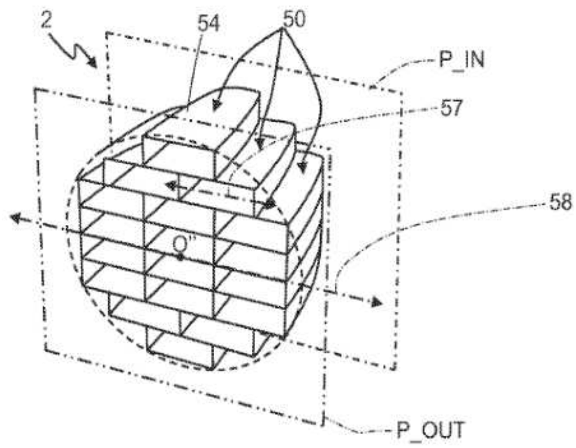


Figure 30 - Overview of the optical concept (from patent number US2014133125A1)

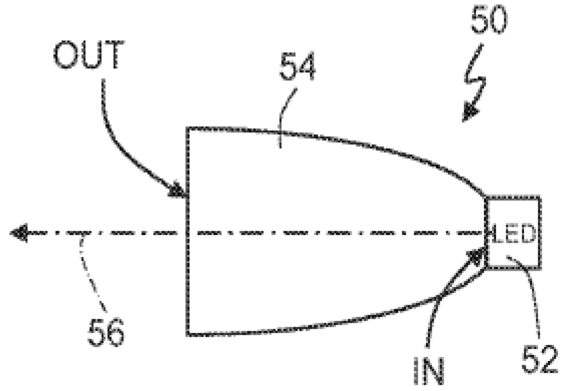


Figure 31 - Cross section of a portion of the light source (from patent number US2014133125A1)

The light source shown in figure allows decoupling the light beam characteristics, and in particular the shape of its cross-section and its divergence, from the shape of the emitting surface, without introducing any loss. The single unit has a rectangular cross-section, and the distances between the centers of output apertures are small compared to the width of the composite light beam formed by the summation of all the unit light beams, this summation occurring because of the propagation of the composite beam and the divergence of each unit light beam. In practice, the unit light beams merge into one composite light beam that has the same rectangular cross-section and the same divergence as a single unit light beam. In other words, at distances which are great in respect to the diameter of the emitting surface, the composite light beam has the same shape and divergence of the beam generated by a single emitting device, since it is formed by a plurality of identical unit light beams which are slightly shifted one respect to the other. Therefore, the final result is a composite beam having a section, in a plane perpendicular to the axis of the composite beam itself and at a desired distance, which is a rectangle of desired area and shape. Furthermore, it is created a light source having an emitting surface which has a circular shape, while producing a rectangular light beam. It should be stressed that the result is not obtained by relying upon a knife-cut aperture and imaging optics as performed, e.g., for standard, theater-like, stage-light projectors, where the beam cut causes high transmission losses.

I reported parts of the patent of which Di Trapani and Magatti are inventors. This patent is, treating a number of critical aspects of the CoeLux product, is also an example of what influence the final specifications, which became:

(1) CCT between 6000 K and 6500 K
with Δuv = -0.001±0.001 (distance from Planckian Locus)

(2) Round emitting area, with diameter comprised in the range:
10-15cm, uniformly fully flashed

(3) Total flux exiting the projector: more than 9000 lm

(4) $R_a > 80$, $R_9 > 65$

(5) Lamp lifetime longer than 20000h; main features (chromaticity & flux) preserved over time

(6) The source should produce a rectangular beam with divergence full angles 10° x 30°

(7) Flat top, possibly sharp edges

(8) Luminous efficiency possibly higher than 50%.

4 - Projector development

a) Optical design and components conceptual demo

LED mixing

As previously reported, the lack of adequate LEDs was really a critical point at the starting point of this work, and no component could fulfill all the requirements at the same time, namely: small dimensions, high brightness, cool white emission and good color rendition. The best compromise found was then to create a mix of bright LEDs creating the correct CCT, good properties of color rendition, high brightness and adequate form factor. The best versatility of course lies in finding the smallest possible package and emitter and, at the same time, having some other advantageous characteristic for this project, for example multiple colors availability.

The LEDs were chosen in the Luxeon Z family, fortunately developed in time for this project, by Lumileds. These are very bright LEDs, available in a series of different colors, with small dimensions and a compact packaging, which makes them suitable for being arranged in array configurations.

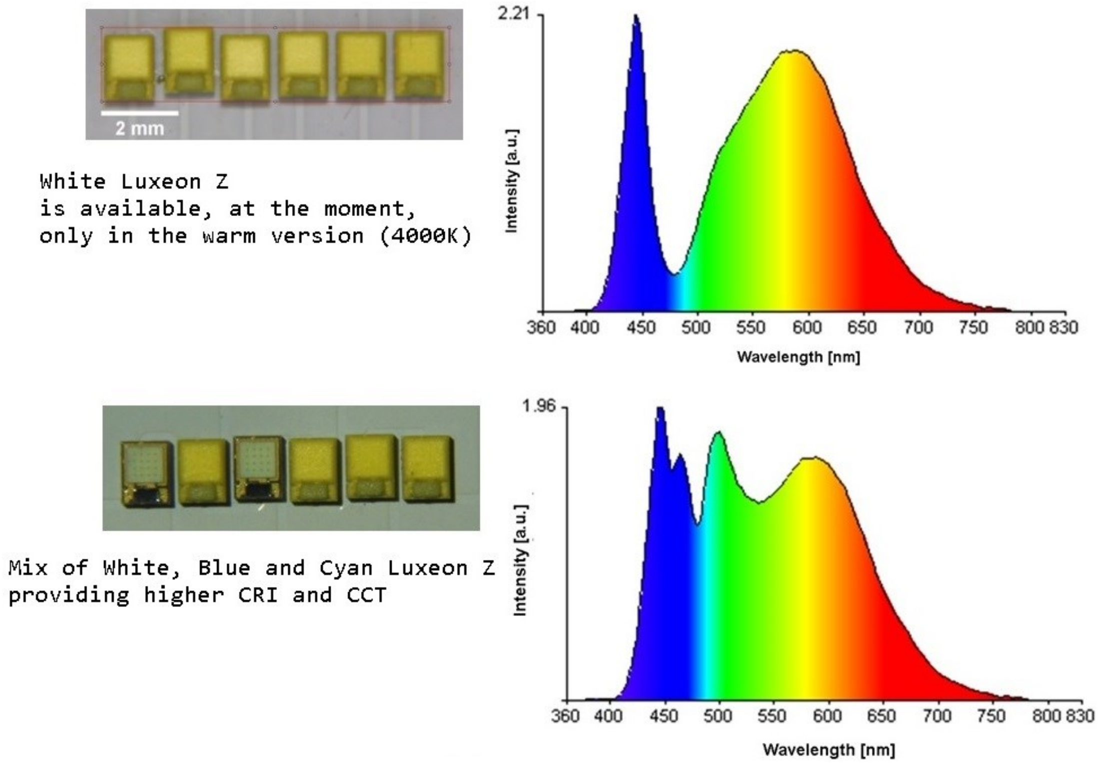


Figure 32 – An example of how mixing different LEDs might help in obtaining a smoother spectral distribution. Notes refer to the availability of Luxeon Z LEDs in March 2013

From easy technical considerations it is interesting to note that a good color rendition might be obtained with a correct mixing even starting from poor single characteristics as visible in Figure 32 (the spectrum obtained by mixing is not the one used in the final prototype). In fact, the final spectral properties will be evaluated by the observer as coming from a single source. However, the total amount of emitted power will be, of course, the sum of powers coming from the different components and, in absence of down conversion or similar phenomena, the final spectrum and energy per nanometer will be simply obtained as a sum of light exiting from the emitters, allowing for simple operations involving chromatic science.

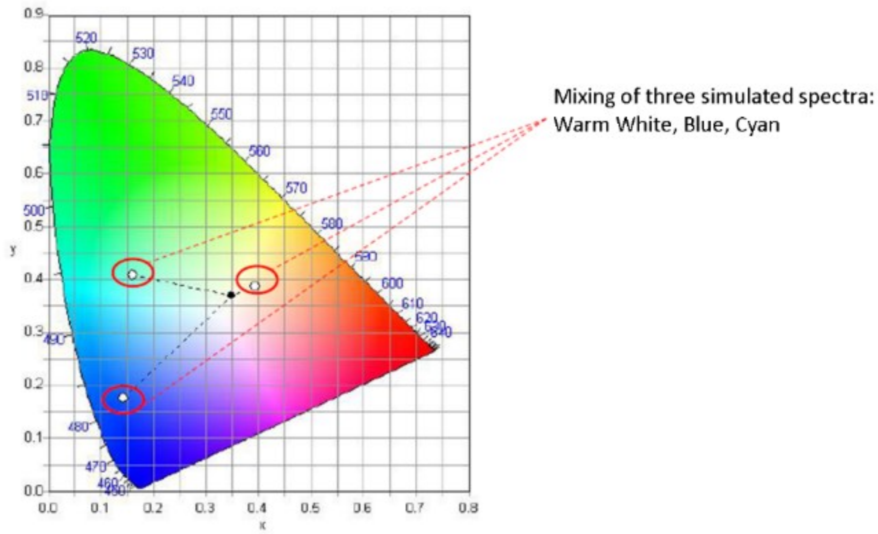


Figure 33

The main point, however, is the fact that in order to obtain an adequate, and high, final luminance, one should employ bright components at least in a significant portion. The conclusion, then, is that a certain amount of white LEDs is needed.

It can be seen the effect of a mixing in Figure 34 and Figure 35. The first was produced during preliminary calculations which I did to explore this solution. The second figure is a plot which contains different measurements I did on preliminary prototypes . There are four peaks in the spectrum, related to the presence of a cool white LED (the external peaks, the pump in the blue region and the yellow phosphor emission) and to the addition of two emitters in the region of blue-cyan wavelengths.

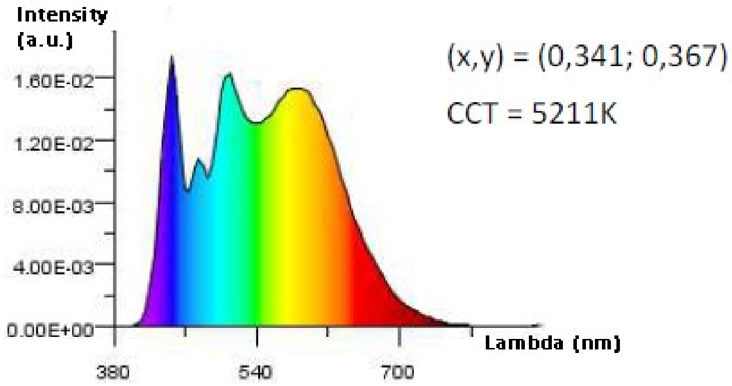


Figure 34 – Calculated spectrum of a LED mix

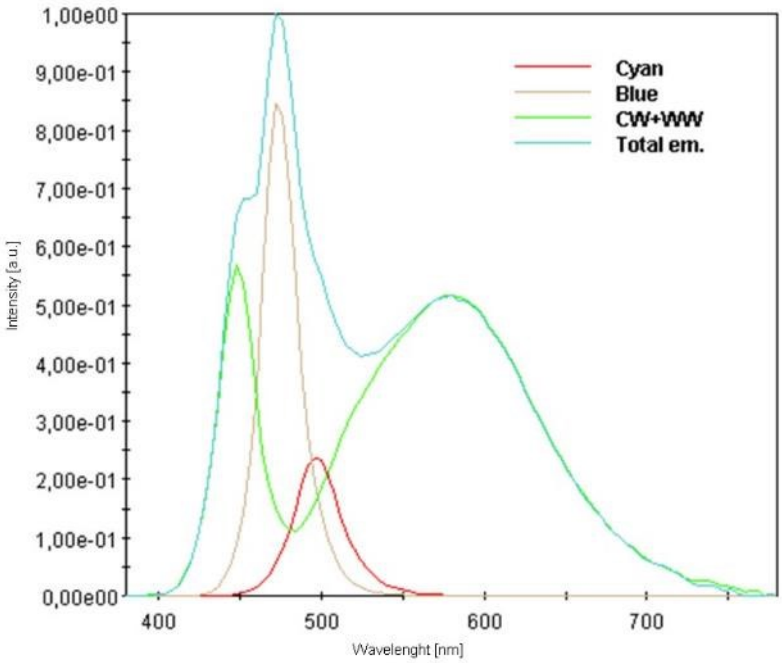


Figure 35 – Spectral measurements of the emitters and of the total emission

Moreover, a color adjustment procedure has been implemented in order to control the spectrum emitted in function of the temperature. This strategy is not completely original, as I learned of this during the research. However, the customization of this strategy for the bright light source was conducted by me, after my proposal to the team. In collaboration with the supplier of the prototypes, I worked both on the implementation of the necessary tools, both for what regards the software (LabView codes) and the hardware (spectrophotometer and physical setup). Moreover, I followed this task up to the final verifications for a correct operability. This control is set specifically for every projector after the assembling, and activated during the functioning. In the first phase, the light emitted by the projector is characterized by a spectrophotometer, then each color channel is adjusted until the targeted emission is obtained and the same procedure is repeated for different temperatures. Each value is then memorized in the projector chip (a matrix, where rows are different temperatures and columns the different channels) and actualized on the basis of a thermal sensor mounted on the board. The effectiveness of such control is visible in Figure 36.

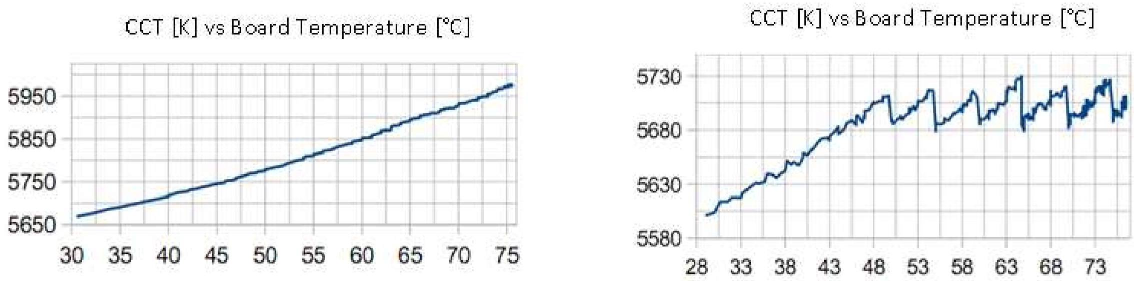


Figure 36 - Comparison of two projectors "CCT vs Board Temperature" with color adjustment procedure OFF (left) and ON (right)

CPC

The light exiting the LEDs is then collimated by a series of CPCs. Such CPCs are specifically tailored to emit light inside a rectangular beam. The exact design of these reflectors has been carried out in a team work with involved also the people from Insubria University, the CoeLux personnel and the supplier. I conducted the actions with the German supplier in an optimization loop which comprehended a number of prototypes with different characteristic. What is here reported is just the final result.

The divergence angles for the two sides of the farfield rectangle were chosen as 10° and 30°. Given a lateral size of the LED of 1 mm, this size determines the dimension of the input aperture for the 10° side and, given the 30° angular aperture for the other side, it thus determines also the other size of the CPC input aperture, the common factor being the total length of the CPC. Thus, a reflector as shown in Figure 37 is obtained, and the smaller aperture is, in principle, the ideal surface where to place light emitters.

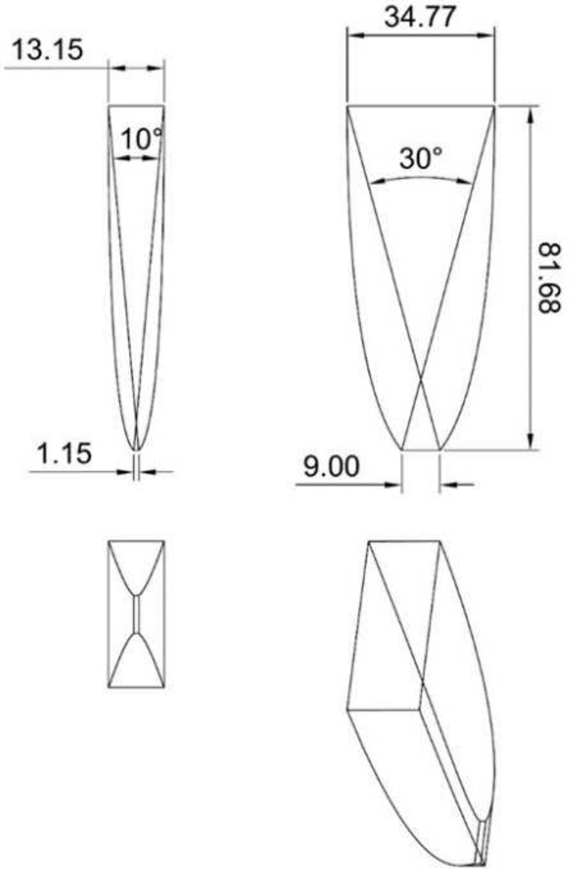


Figure 37 - Single CPC technical drawing (dimensions in mm). This drawing was realized by G. Gatti

A set of 6 LEDs fits the input aperture of each CPC and 34 CPCs are used in the projector. Metal CPCs made of high reflectivity Alanod Miro Silver 27 are used. The figure here below shows the dispositions of the array of LEDs at the input aperture of the CPCs, followed by a picture of the first prototype of the same (Figure 38, Figure 39). Then, there are: a picture of the first prototype of the assembled reflector (Figure 40), constituted by a number of CPC and alignment masks; the analysis of the far-field projection of the same (Figure 41); the appearance of the multireflector when seen from a variety of viewing angles (Figure 42).

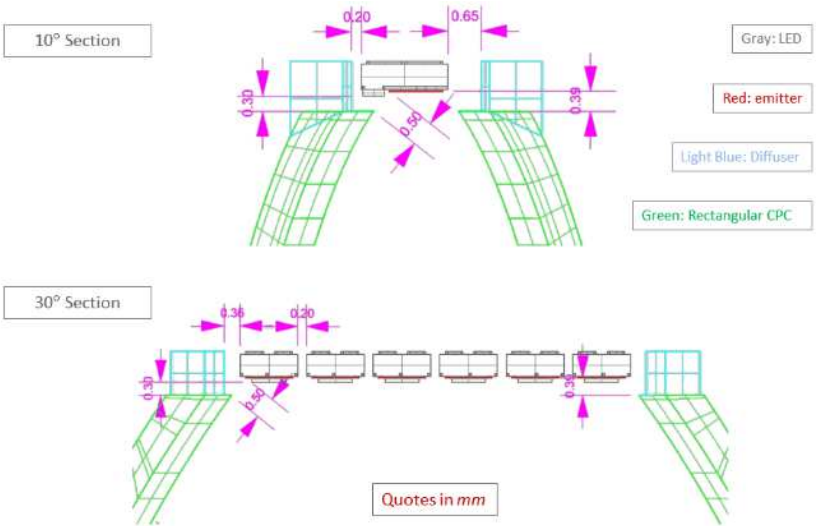


Figure 38 - Technical design of CPC aperture positioning with respect to LED array. Drawn by G. Gatti

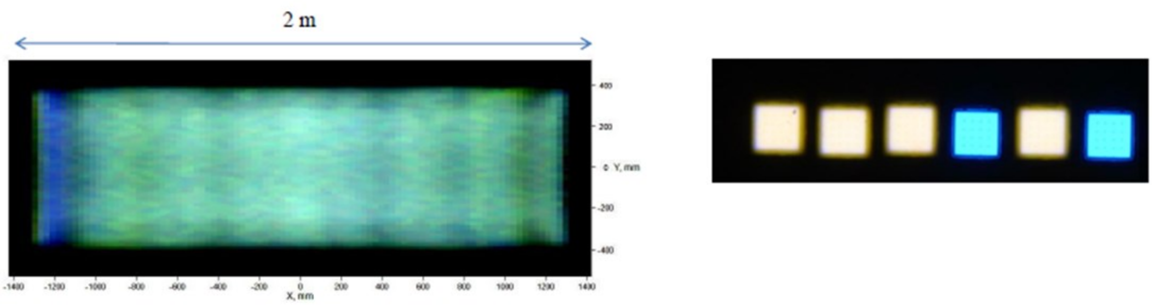


Figure 39 - LED array (right) positioned in a CPC and conjugated far field (left)

Figure 40 - Picture of the first assembled reflector

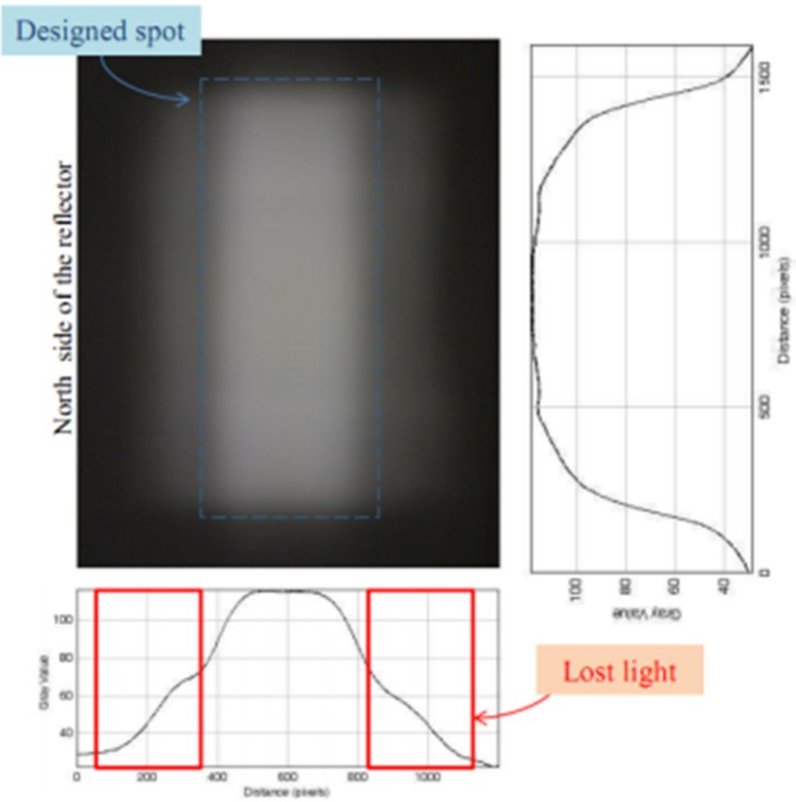


Figure 41 - Optical evaluation of the first prototype of a CPC reflector obtained

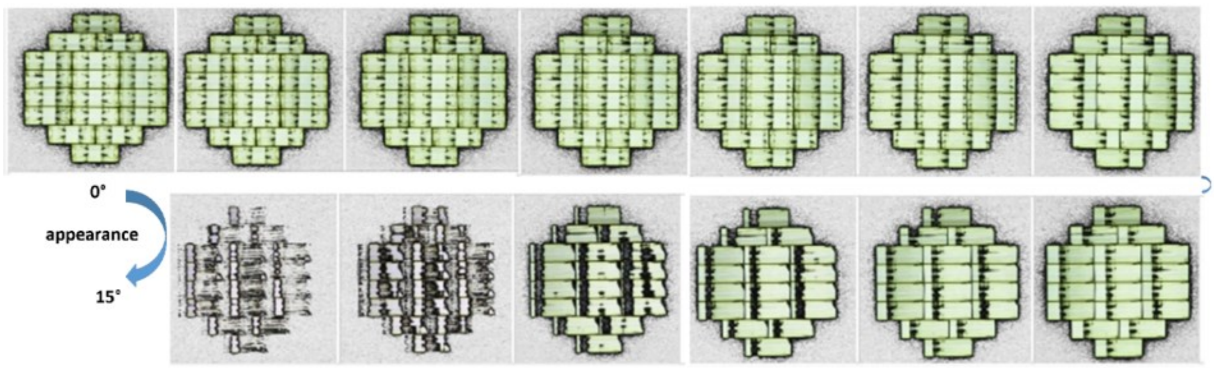


Figure 42 - Appearance of a multi-reflector assembly

b) On the way: tests and technical problems

The design developed should be put into effect by means of a functional assembly. The Figure 43 exhibit the conceptual structure of the light source; beyond the fact that there is no detail of the optical design, it shows the necessary parts for creating the light source itself: without these components, the project would not be functional at all as a product.

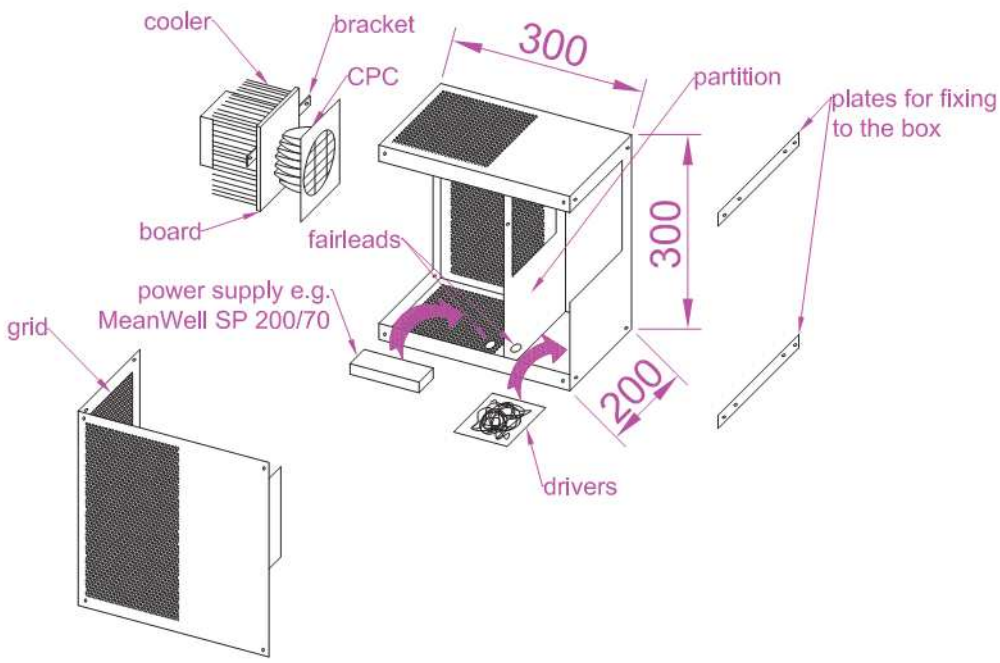


Figure 43 - Conceptual exploded drawing of the light source

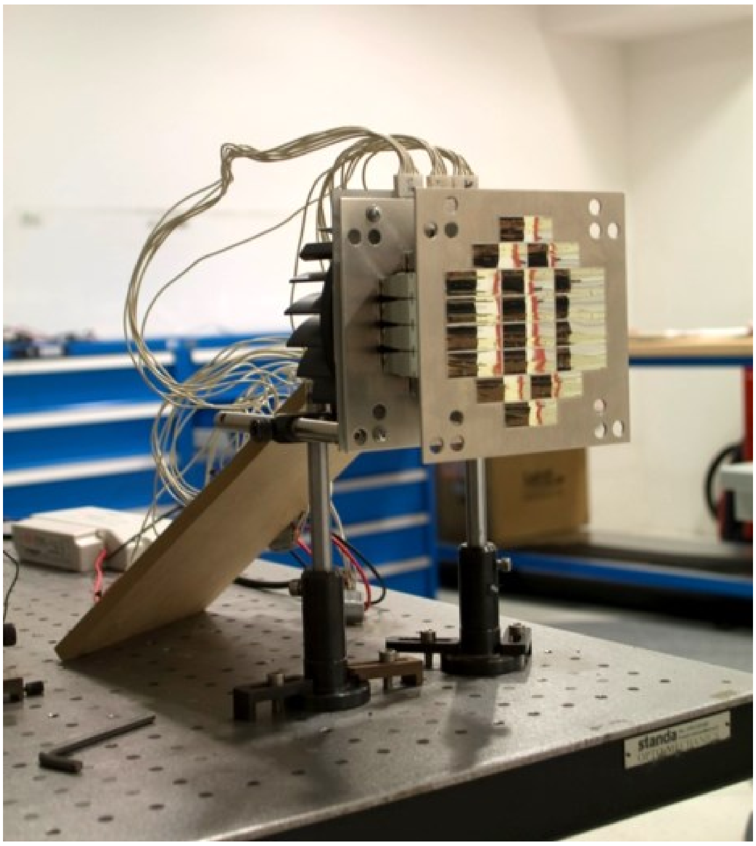


Figure 44 - Preliminary assembly, testing the concept of the light source

A preliminary test performed in laboratory is visible in Figure 44, where a prototype of the reflector (with smaller dimension) is mounted on a test board with a temporary heatsink and was used by me for preliminary characterizations.

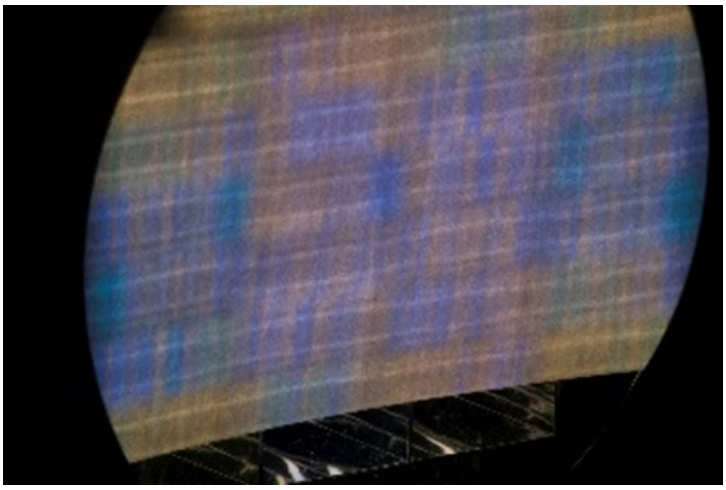


Figure 45 - Near field of the prototype visualized by a diffuser

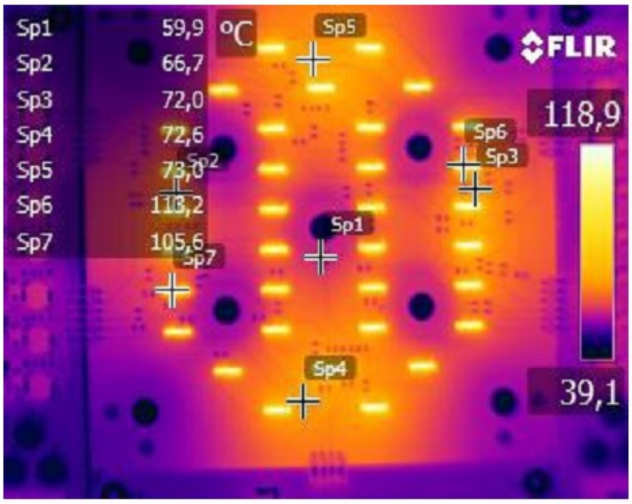


Figure 46 - IR camera thermal measurement of the LED board

A multitude of characteristics have been explored, studied and optimized with pre-prototypes; it is worth reporting here a simple and significant example which I refer to as "DispE". Such a sample was a tentative disposition of LEDs in order to obtain, starting from multiple colors, a uniform projection. While a number of conditions were imposed on such a design, a notable mistake drove the test to a significant result, where a clear non-uniformity along the vertical direction was clearly visible (see Figure 47).

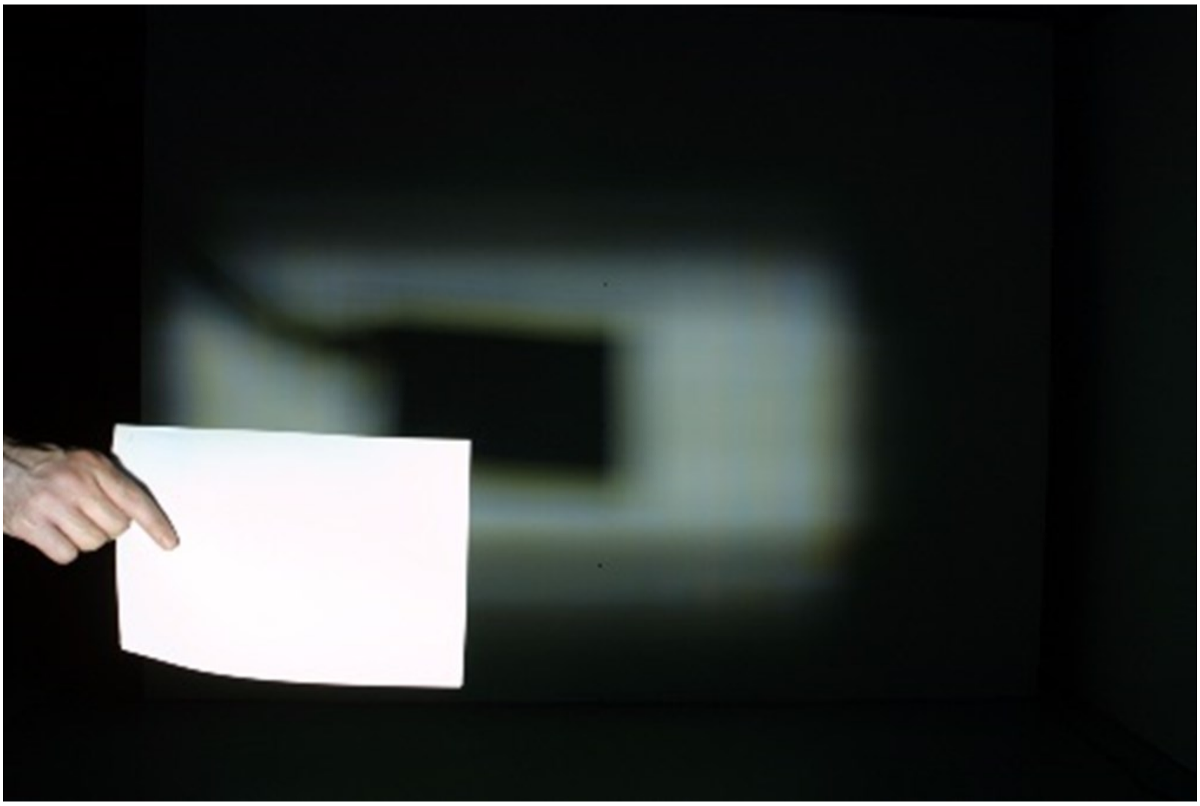


Figure 47 - Colored shadows of DispE prototype

Figure 48 - Scattering from the reflector, making visible color disuniformity of DispE prototype

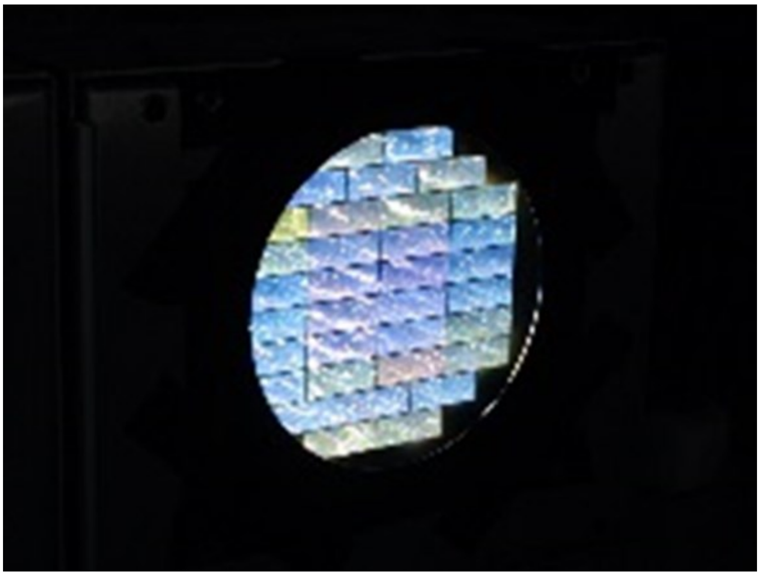


Figure 49 – Scattering from the reflector, showing an alternative board with non-uniformity issue meliorated

c) Prototype 1

The definitive board layout is reported in Figure 50: an appropriate mixing of Cool White (CW), Warm White (WW), Green (G) and Blue (B) LEDs is disposed on a map composed by 34 arrays that match the input apertures of the designed optic. Notably, this disposition designed by me, precisely the disposition of every color track, allows for a good color uniformity both in the near field (visualized by the barycenter of colored boxes) and in the far field (as fathomable from the balanced disposition in places from 1 to 6).

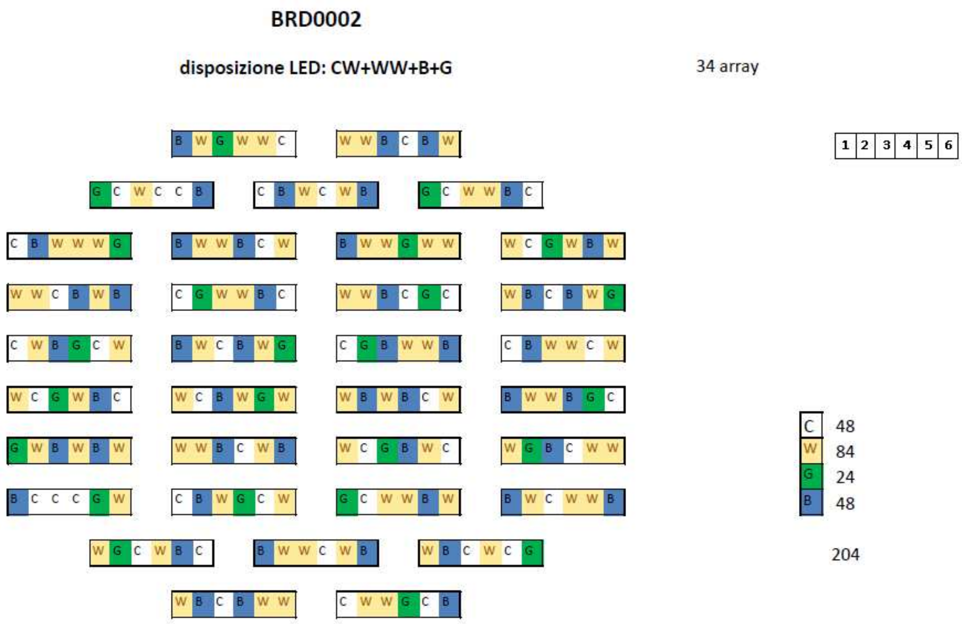


Figure 50 – LED disposition on the board

An immediate visualization of the meaning of different tracks is achieved switching on just one of these, as visible in Figure 51, both in picture and in the relative scheme. It is worth noting here that such a structured design might present, at least in principle, more possibilities of failure. An example is here reported (Figure 52) a picture where, in fact, a single blue track was not working and such a failure was detected.

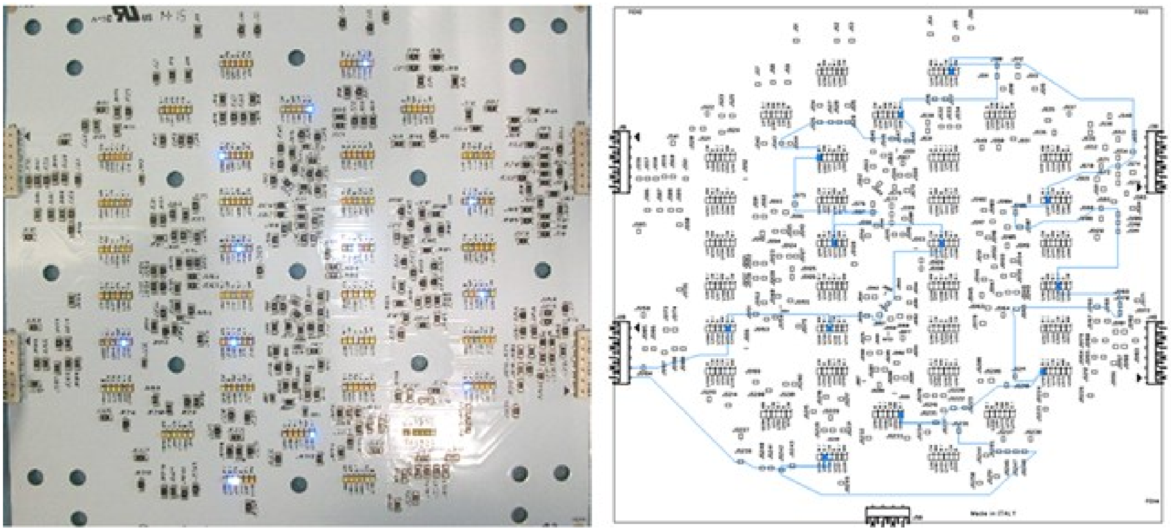


Figure 51 - A single blue track switched on

Figure 52 - A failure of a blue track

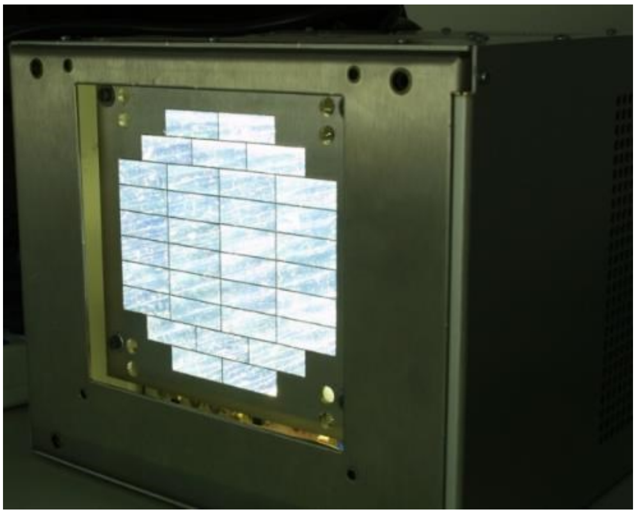
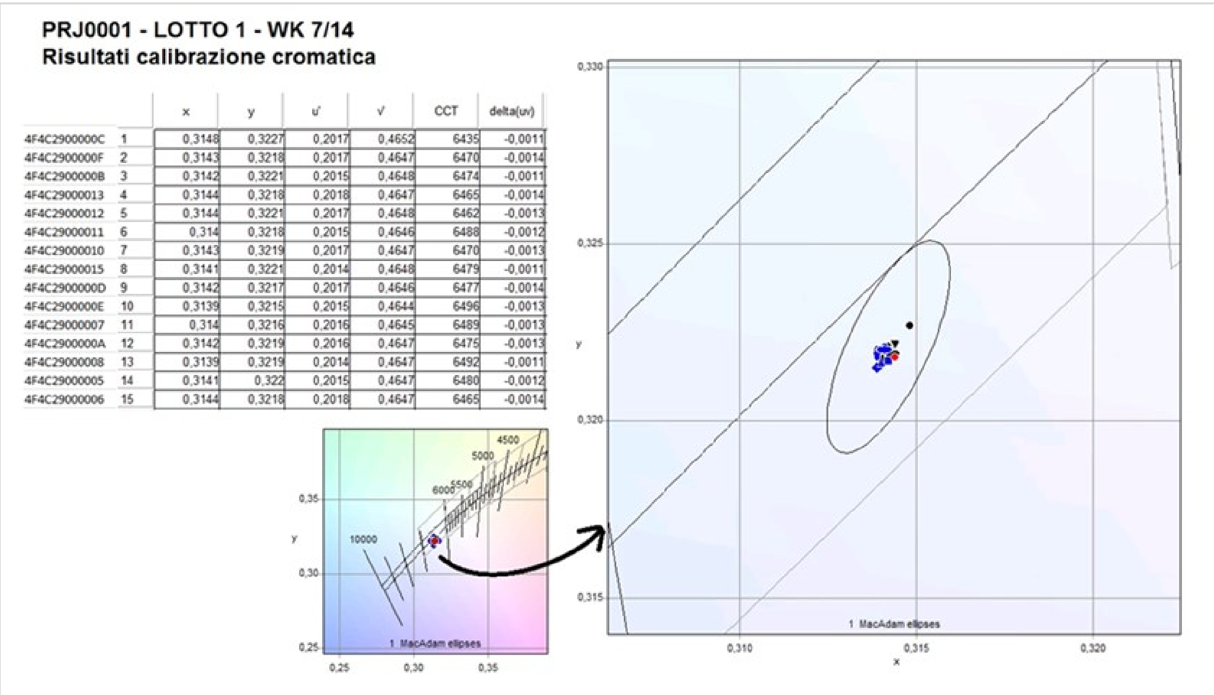


Figure 53 - Prototype 1 – first version

As visible in Figure 54, by means of the calibration of colored LEDs, a wonderful result has been obtained in 2013, giving the first batch of light sources with the same perceived color and largely acceptable flux differences.



PRJ0001 - LOTTO 1 - WK 7/14
Risultati calibrazione cromatica

		x	y	u'	v'	CCT	delta(uv)
4F4C2900000C	1	0,3148	0,3227	0,2017	0,4652	6435	-0,0011
4F4C2900000F	2	0,3143	0,3218	0,2017	0,4647	6470	-0,0014
4F4C2900000B	3	0,3142	0,3221	0,2015	0,4648	6474	-0,0011
4F4C29000013	4	0,3144	0,3218	0,2018	0,4647	6465	-0,0014
4F4C29000012	5	0,3144	0,3221	0,2017	0,4648	6462	-0,0013
4F4C29000011	6	0,314	0,3218	0,2015	0,4646	6488	-0,0012
4F4C29000010	7	0,3143	0,3219	0,2017	0,4647	6470	-0,0013
4F4C29000015	8	0,3141	0,3221	0,2014	0,4648	6479	-0,0011
4F4C2900000D	9	0,3142	0,3217	0,2017	0,4646	6477	-0,0014
4F4C2900000E	10	0,3139	0,3215	0,2015	0,4644	6496	-0,0013
4F4C29000007	11	0,314	0,3216	0,2016	0,4645	6489	-0,0013
4F4C2900000A	12	0,3142	0,3219	0,2016	0,4647	6475	-0,0013
4F4C29000008	13	0,3139	0,3219	0,2014	0,4647	6492	-0,0011
4F4C29000005	14	0,3141	0,322	0,2015	0,4647	6480	-0,0012
4F4C29000006	15	0,3144	0,3218	0,2018	0,4647	6465	-0,0014

Figure 54 - Projectors emission: the perceived color of every sample of the first production batch is satisfactorily near the targeted color (1MAE is also depicted)

Prototype 1: a necessary revision

Even if the following detail have been evaluated before starting the design, the first version of the prototype showed a lack in performance. In fact, the discretization of the LED sources in the input aperture of each CPC emerged immediately as significant problem during early tests. The strategy of color mix aimed at obtaining the target spectral properties had the drawback of some illuminance and color structures in the farfield, i.e. in the light distribution impinging on the target. In Figure 55 is presented the light beam of such a prototype, where significant colored structures are visible, in the far field of the projector (picture taken by me in a testing environment). The Figure 56 is the colorimetric analysis of the same, in false colors, in order to enhance the same colored structures.

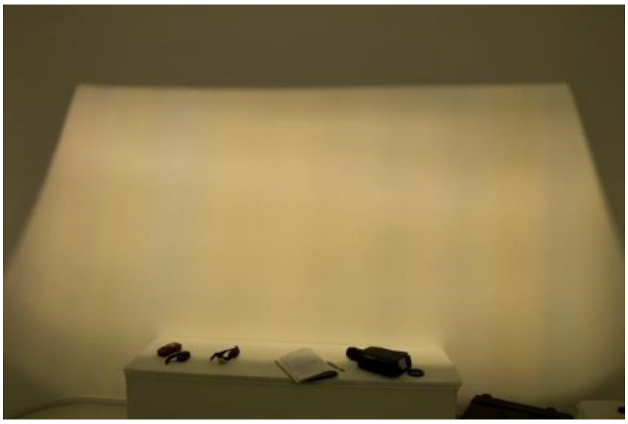


Figure 55 - Projected light beam

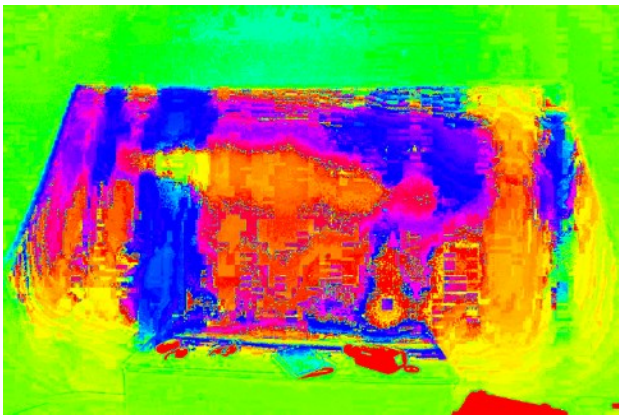


Figure 56 - Hue analysis of the projected light beam

These figures are shown here in order to better comprehend the implication of such a imperfection in this work. In sequent figures, the correct analysis is reported, showing the exact size of this modulation.

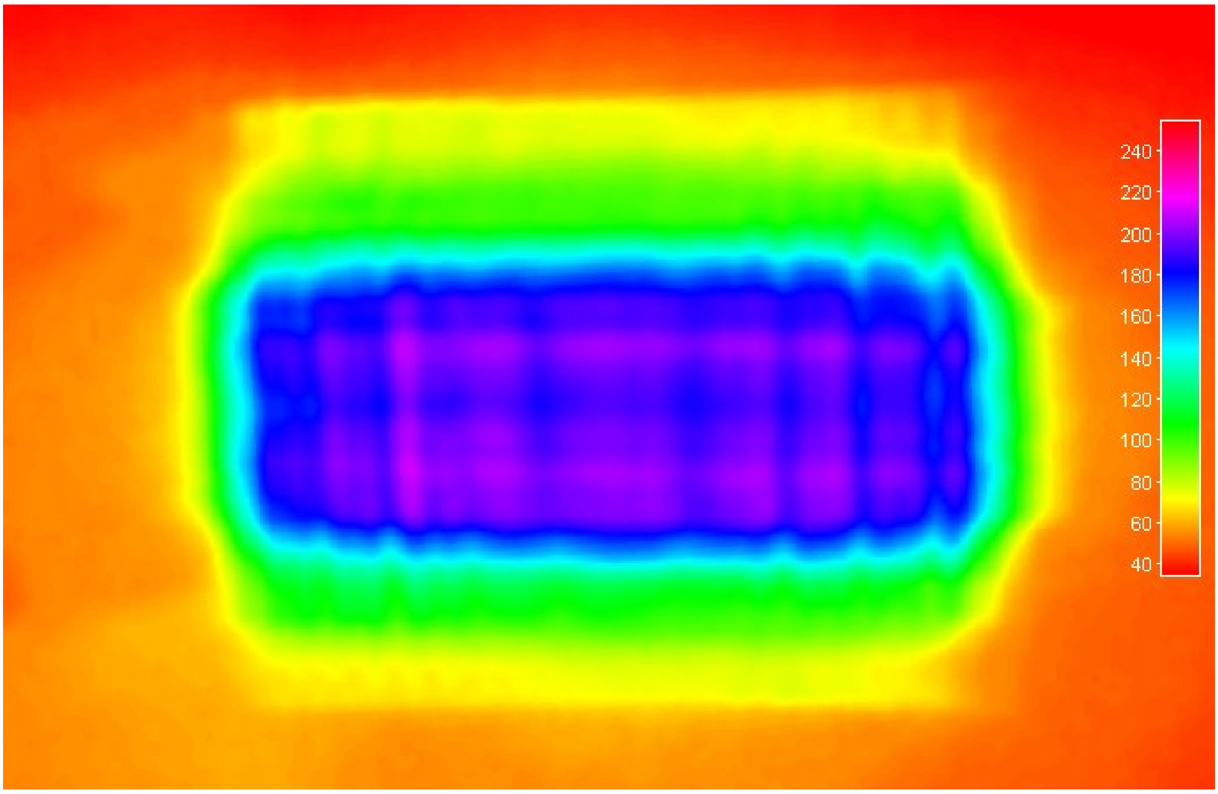


Figure 57 - Far field of the light beam, where is clearly visible the 30x10 ° main beam in which modulations are present

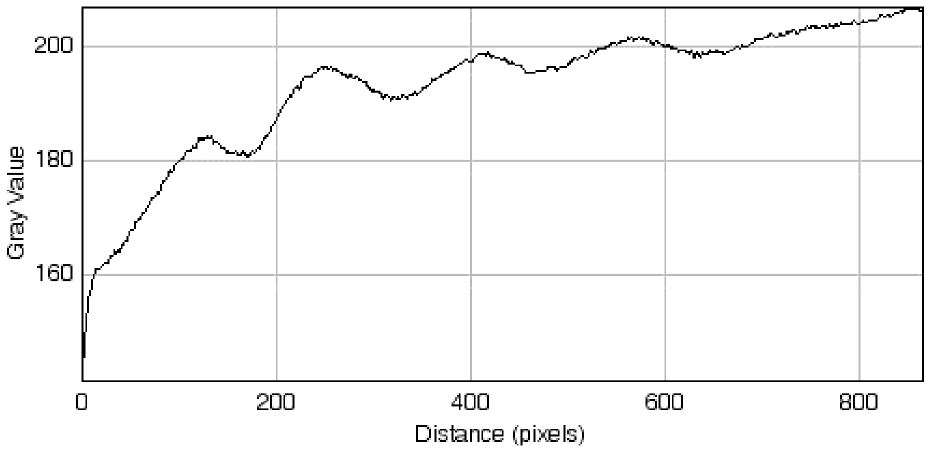


Figure 58 - Graph of the intensity value in the central horizontal section of the beam

In fact, starting from multiple sources, differently colored, one should take into account what follows:

- the mixing of the far field radiation (uniformity in function of the angle) is what define the uniformity of the light spot. This may be easily obtained by means of a proper diffusor, but efficiency is the critical parameter
- having an emitting surface which produces a colored pattern in the near field, possibly will result in colored penumbras (Miñano, Benítez, Mohedano, & Alvarez,

2013). In fact, as well as multiple shadows are due to the presence of more than one light source, colored penumbras may originate from colored sources. It is worth noting here that the subtended angle is criterion to evaluate the final effect expected.

Interestingly, a uniform far field can also be achieved by using a fly’s eye integrator; here the solution is not analyzed in detail, and just a simple description follow, showing the effect obtained. The underlying concept is known in optics and described as useful for different applications. It is also named after Kohler, typically when engineered for instruments devoted to microscopy. The design of this component has been developed by CoeLux Srl, whereas I was in charge of integrate this component on the light source. The effectiveness of this solution has been thoroughly discussed in the team involved, before, during and after the development and, notably, the developed solution brought also to a new dedicated patent application, in which I was not directly involved.

The final design of the fly’s eye integrator developed for this project resulted in a single PMMA block with lenslets on both sides. The thickness of the layer corresponds to the (internal) focal length of the lenses on both sides. In order to obtain a rectangular farfield, rectangular lenses are needed; the aperture of the lenses is 1.7mm x 0.65mm and the thickness of the layer is 5mm.

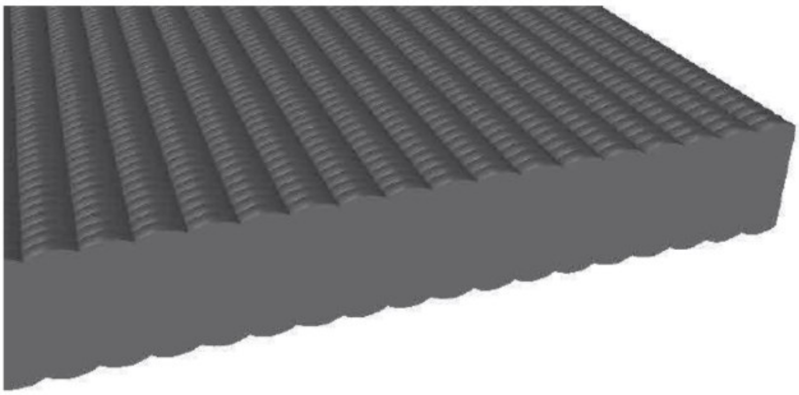


Figure 59 - Fly's eye integrator as designed by CoeLux Srl

The fly’s eye layers can be produced by injection molding with a tool made with ultra-precision diamond milling technique. Precise alignment of the parts constituting the molding plate is needed to ensure good performances of the fly’s eye integrator.

Since the angular distribution of the light entering the fly’s eye integrator closely matches the angular distribution determined by the aperture of the lenses, when an observer looks into the projector the appearance is “fully flashed”, except for the most external lenses. This design allows then for the compliance with the optical requirements improving significantly the final performance.

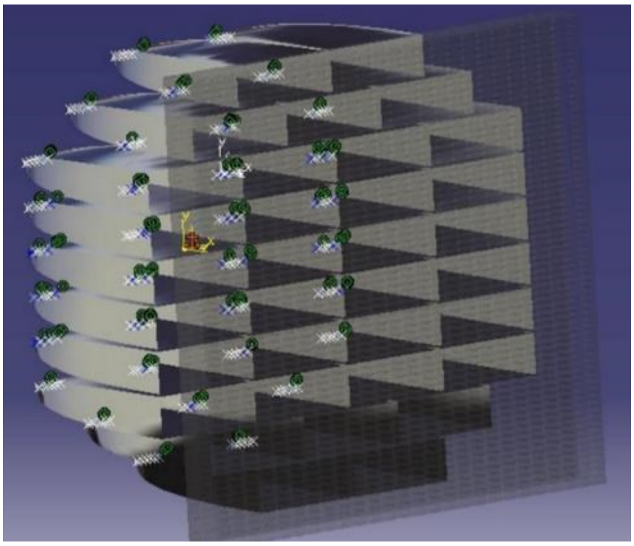


Figure 60 - 3D drawing of the positioning of the optical integrator (by CoeLux)

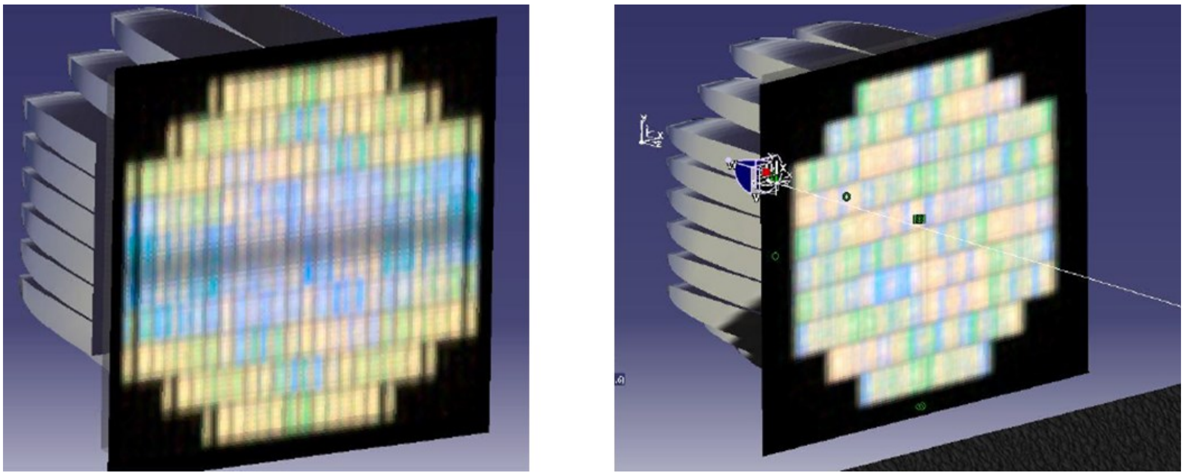


Figure 61 - Lenslet colored pattern in two cases: wrong DispE and correct prototype (by CoeLux)

Figure 60 and Figure 61 show screenshots of the simulations produced by CoeLux Srl. Actually, also because of the significant investment required, an intermediate test took place, which was conducted by me and A. Lotti, and, as visible in Figure 62, a small prototype of such an integrator has been tested before proceeding in creating the definitive mold.

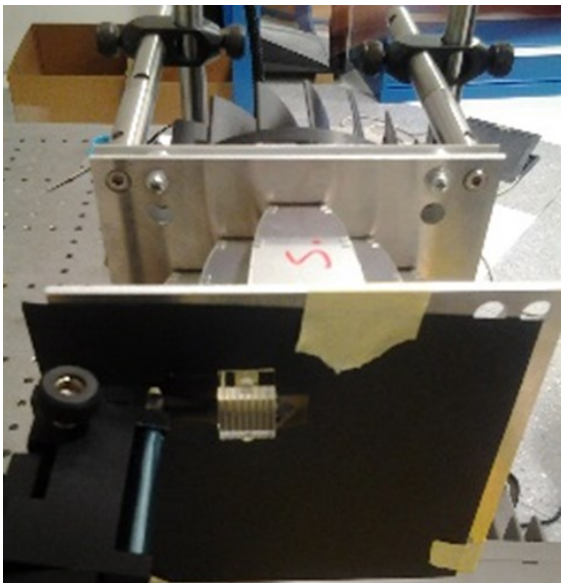


Figure 62 - Intermediate test of the fly's eye integrator

The effectiveness of such a solution is clearly visible in Figure 63.

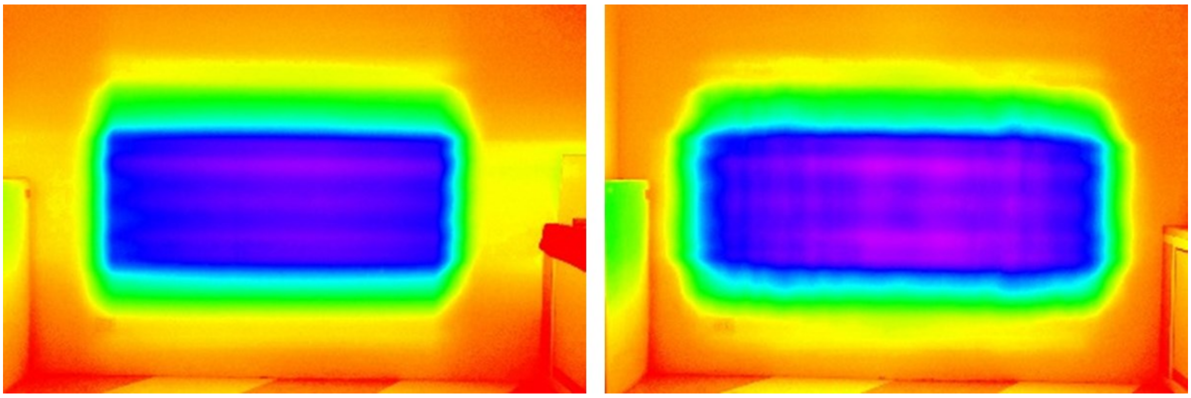


Figure 63 - Comparison between far field radiations with the new component (left) and before (right)

d) Prototype 2

The figure here below shows a technical design of the final output aspect of the projector, and a blown-up view of all the constituting elements. In particular, the external case with a circular aperture and the internal block comprising the optical components (the CPC array is clearly visible in the image), the electronic board and the heat sink. This design integrates the reported improvement as well as other not reported.

Noteworthy, two similar versions of the Prototype 2 were actually realized: the second differing from the first thanks to the introduction of new LEDs. Such LEDs were not available during the course of the present research (as cited above), being developed in 2015, and were available to CoeLux Srl. I was in charge of coordinating also these different versions. Notably, such white LEDs show high color rendering properties and harvest the results of technological evolutions, turning out to be even more efficient and with longer lifetime. Finally, there is no need (nor chance) to carry out a calibration process. In fact, the latter characteristic is not fully positive: what is behind is the reliability of the binning process that, as explained above, is not totally under control of the customer (i.e. the manufacturer of the projector). As a consequence it is not possible to replicate what is shown in Figure 54.

Then, the second version, while showing interesting characteristic, is not fully characterized in this work. In Figure 70, however, labeled as PRJ2, is compared with the first version (mix of different LEDs) and the chromatic advantages are highlighted.

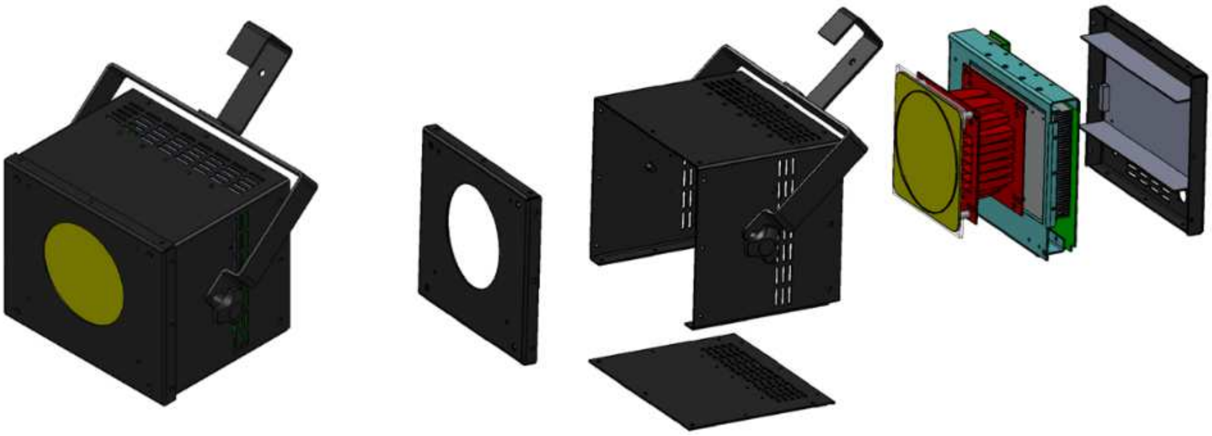


Figure 64 - Exploded drawing of the second prototype

Figure 65 - Picture of the second prototype

5 - Source Validation

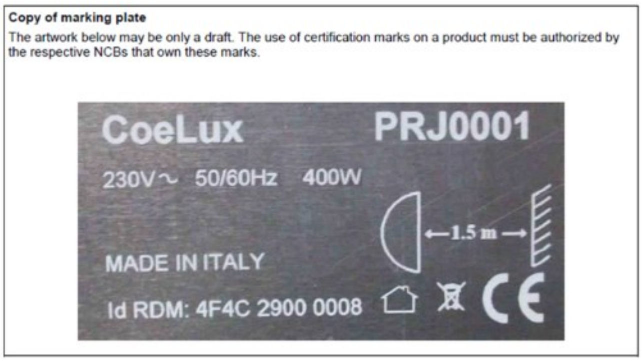


Figure 66 - Copy of the marking plate of the final light source

Both prototype 1 and prototype 2 have been characterized by me in detail, also with the support of CoeLux Srl and certified external laboratories, checking performances and compliance with targets. In Figure 66 the marking plate of the final light source is shown, which comprises the identification codes, electrical parameters and the symbols required by the law. In the following sections are reported principal measurements on the source, a brief characterization of the effect when tested on the CoeLux system and the most significant parts of tests conducted in an accredited laboratory regarding the compliances.

a) Functional characterization

Emission characterization: color and brightness

During the course of the work, the expectation on the total flux was high (18000 lumens) because of underestimation of thermal drop on LEDs, and overestimation of the efficiency of the reflector. Tests (Figure 67, Figure 68) confirmed that the real luminous flux of prototypes is equal to 11000 lumens, that is, however, more than the required value. Moreover, the intensity values and distribution completely reflects the expectations. It is worth citing here that also the stability of the emitted light is impeccable.

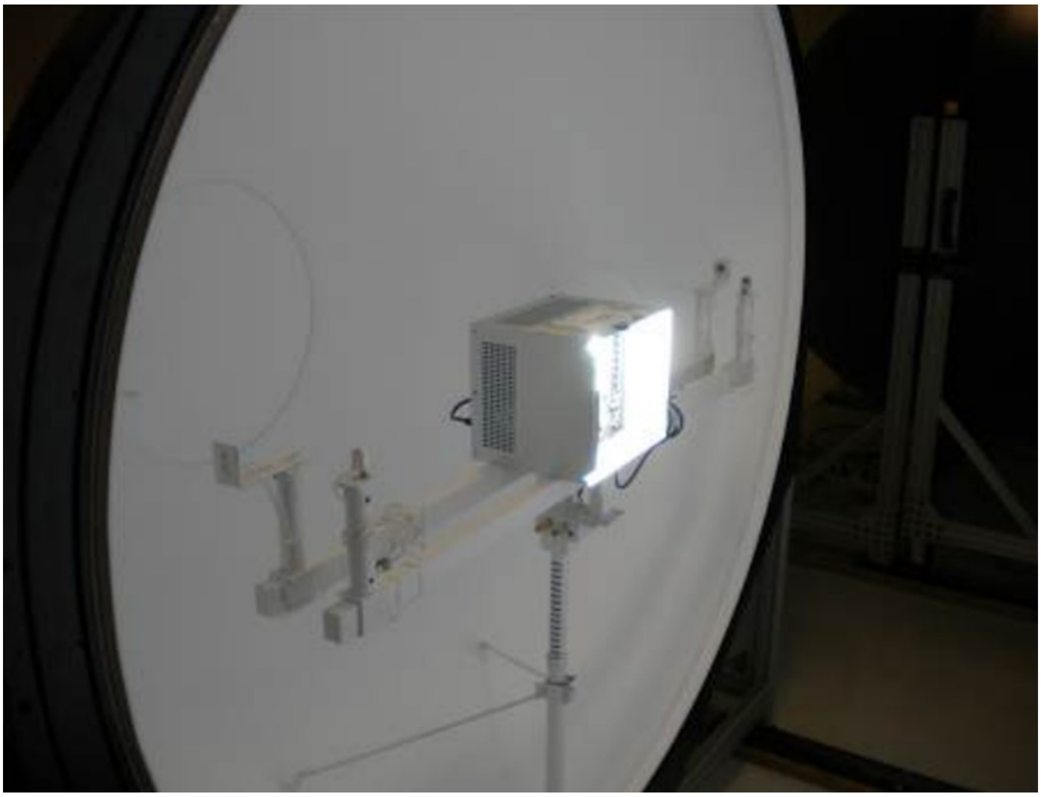


Figure 67 - Measurement of the total luminous flux of the projector, using an integrating sphere

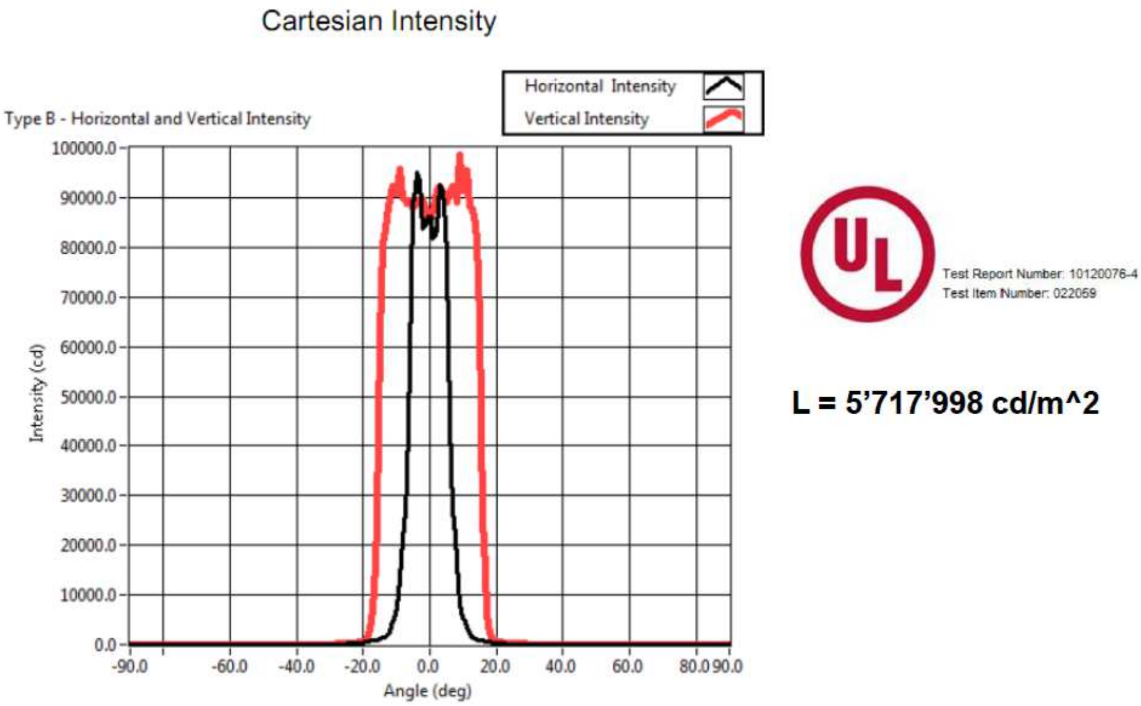


Figure 68 - Measurement result of the intensity of the projector

For what concern the uniform, fully flashed, appearance of the light source, the result is shown in Figure 69, and it is interesting to compare it with Figure 13. The round clipping is obtained downstream with an additional mask.

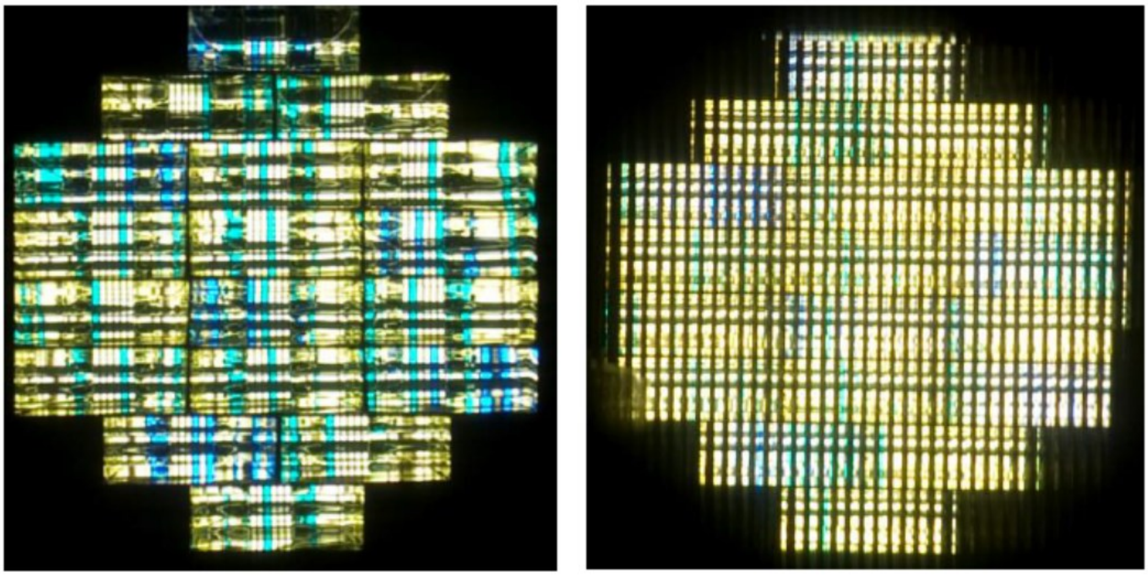


Figure 69 - Appearance of Prototype 1 before (left) and after (right) the implementation of the additional optic

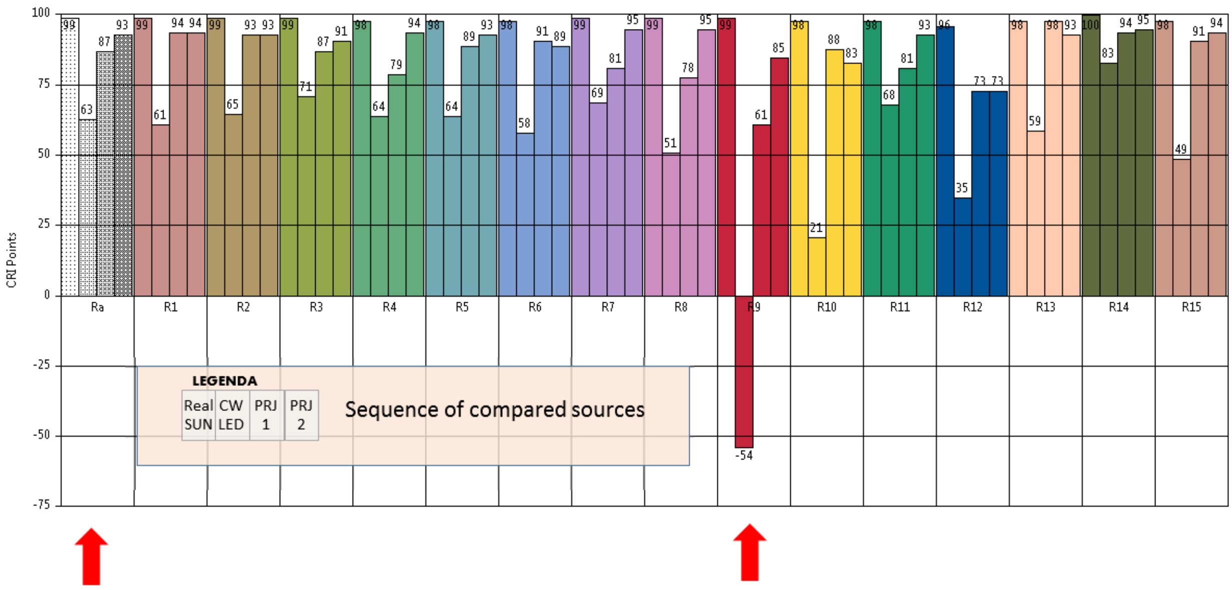


Figure 70 - Comparison of Color Rendering Indexes of four different light sources (description in the text)

As already cited above, the chromatic indexes evaluation clearly indicates that the obtained result is by far better when compared with simple Cool White LEDs. The absolute values are very interesting and adequate to the purpose of this work.

Figure 71 - The appearance of a CoeLux system swithced off

Figure 72 - The appearance of a CoeLux system swithced on

As seen in the reported figures, the effect of natural daylight coming through a window is perfectly achieved. The visual aspect of a sun image is also obtained. The sun apparently follows the observer moving inside the room.

Measurements of the spectral properties of the direct light from the artificial sun and the diffused light of the artificial sky were performed in different position inside the room.

The results confirmed that the spectral content of the light inside the room changes for different observation positions. In particular, the zones inside the direct light are illuminated by light with a lower correlated color temperature (CCT) than the zones in "shadow" areas.

Figure 73 - Picture of a room lit by a CoeLux system

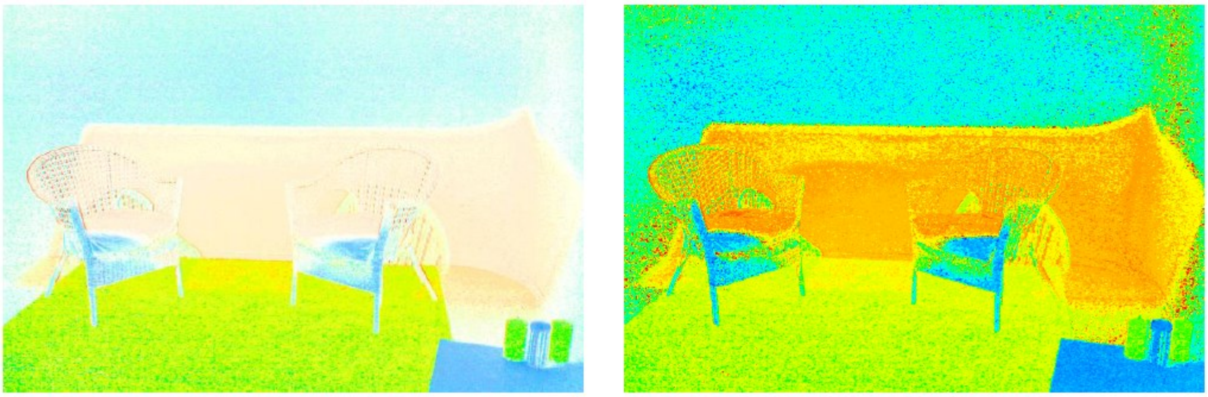


Figure 74 - Color analysis of the previous picture (description in the text)

Figure 74 is the color analysis of the picture of Figure 73. The picture was taken with white point at 5200 K. In the picture on the left of Figure 74 the brightness of each pixel was set to its maximum value, then what is shown is an image where luminance has been normalized for every pixel and in the picture on the right also the saturation was set to its maximum value. Therefore the picture on the right shows the hue of each pixel, to highlight the different directional distribution of the two components of the light produced (sun and sky). For the white zones in the room, the color shifts towards the orange/yellow inside the direct beam and towards the blue for the zones in the shadow.

Further examples are shown: these pictures clearly show how the environment in the room itself influences the color properties of the room, since the surfaces over which the direct light impinges act as secondary diffused-light sources. In particular, as visible in the bottom row of Figure 75 the marble top of the washbasin acts as a secondary source for the room and also as a secondary source to illuminate a person standing in front of the mirror.

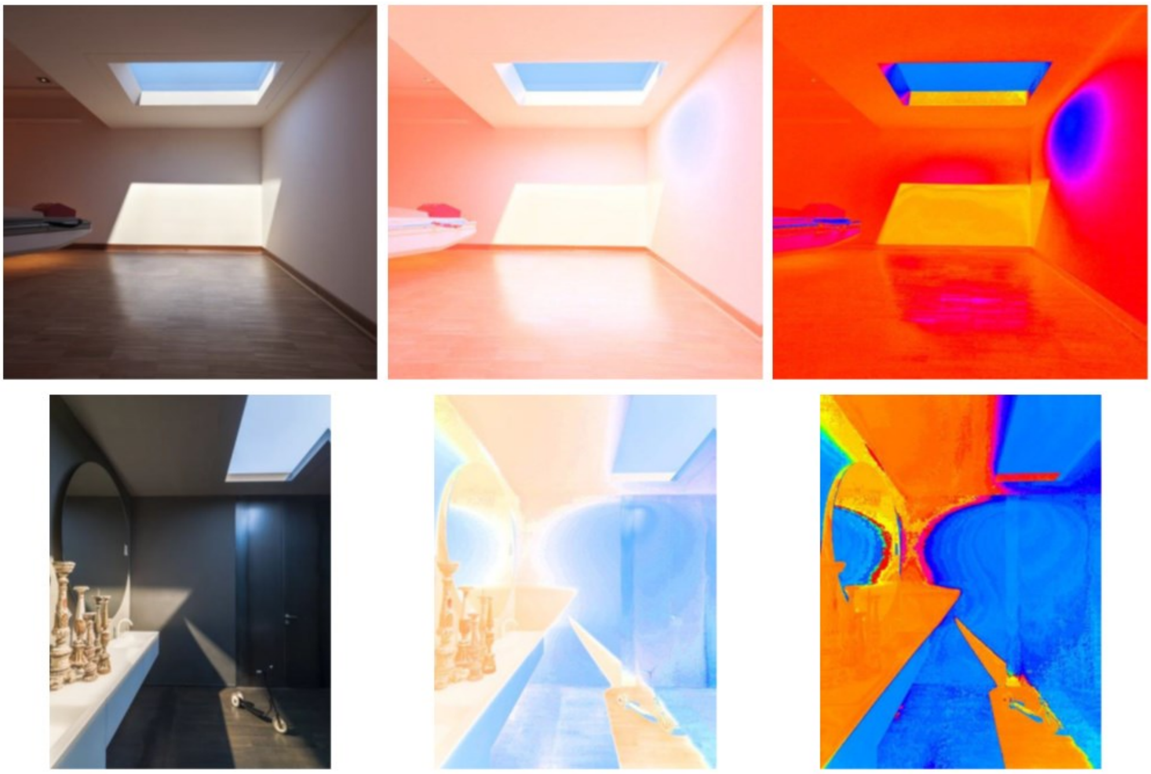


Figure 75 - Picture and color analysis of the installations in Humanitas hospital and Boffi Showroom

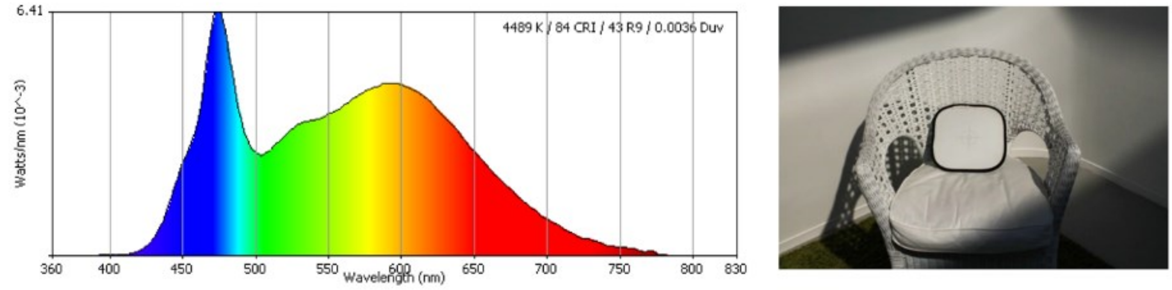


Figure 76 - Spectral measurement in a sunny zone

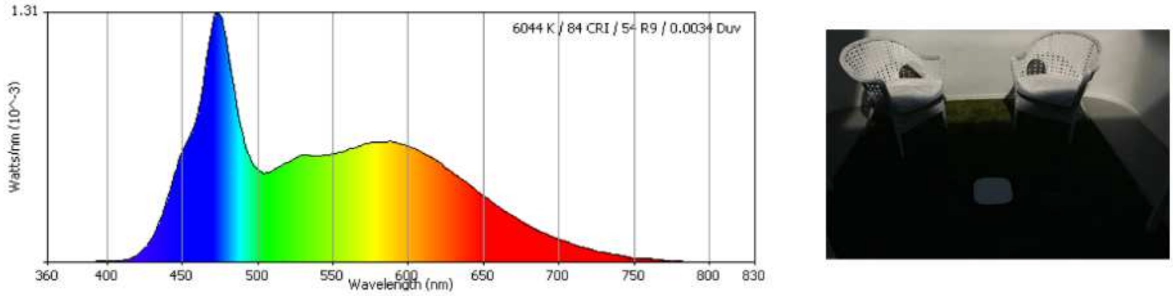


Figure 77 - Spectral measurement in the shadow

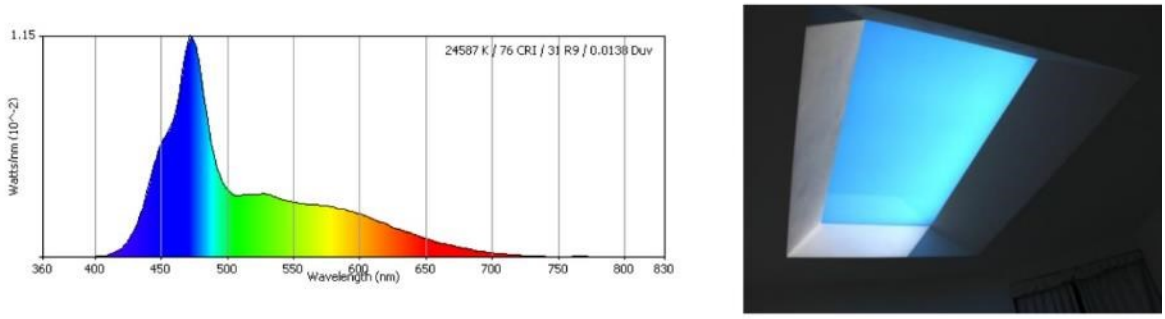


Figure 78 - Spectral measurement of the sky

For the quantitative measurements a white calibration target for photography was used.

Figure 76 shows the spectrum measured with a spectrophotoradiometer on the white target inside the “sunny” zone shown. The CCT is roughly 4500 K, with color rendering index $R_a = 84$ and rendering of dark red color $R_9 = 43$. These numbers guarantee high chromatic properties of the light, which results from the combination of the direct component and the diffused component. Analogously, in Figure 77 and Figure 78, are reported the measurements in a zone in the shadow, where a mix of the two principal components is mainly visible, and of the pure sky.

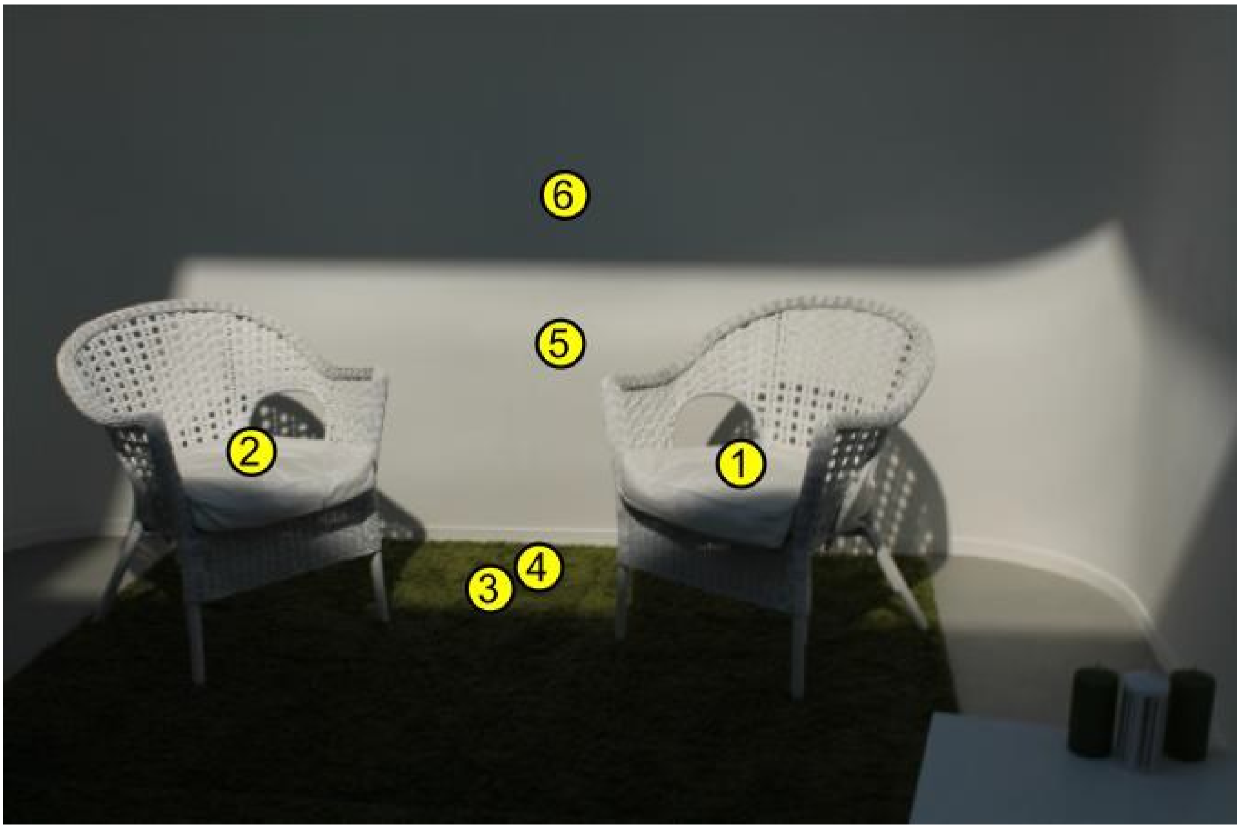


Figure 79 - Illuminance measurements

A series of illuminance measurements were performed (both horizontal and vertical illuminances), evaluated by mean of a luxmeter.

The results for these exemplary points are the following:

- Point 1: Horizontal illuminance = 1002 lux
- Point 2: Horizontal illuminance = 1025 lux
- Point 3: Horizontal illuminance = 934 lux
- Point 4: Horizontal illuminance = 1020 lux
- Point 5: Horizontal illuminance = 1080 lux, Vertical illuminance = 800 lux
- Point 6: Horizontal illuminance = 157 lux, Vertical illuminance = 153 lux

The conclusion is that for standard mounting height of the lighting system, the illuminance level inside the direct light spot is around 1000 lux. The vertical illuminance in the room at the level of the eye of an observer is around 150-160 lux.

As verified in the next chapter, these values are adequate to mimic a window through which the Sun enters and lit the room. Despite the fact that the illuminance values are lower with respect to an analogue real situation (a factor of ten at least), the perception of the scene is undoubtedly recreated.

Finally, a complete measurement of the luminance of the room has been performed by means of a luminance camera.

Figure 80 - Luminance measurement

b) Certifying the solution

Certification: beyond the demonstration of the solution

The source, object of this work is, in fact, a component of a recessed luminaire that should be compliant to the requirements for such a category. Directives and regulations should be applied according to government laws. The conformity required can be proved using harmonized standard and the entire list is here reported for the sake of completeness; the most significant requirements in fact driven this work from the starting steps and have been previously identified.

In the EU, the essential requirements are stated by Directive n. 2006/95/CE (Luminaires SAFETY) and Directive n. 2004/108/CE (Luminaires EMC). With respect to the first one, standard applied were:

- Recessed luminaires safety: EN 60598-2-2:1998 used with EN 60598-1:2008 + A11:2009
- (Component) LED module: EN 62031:2008

- (Component) Power supply: EN 61347-2-13:2006 with EN 61347-1:2008 + A1:2011
- Human exposure to electromagnetic fields: EN 62493:2010

- In particular and as cited before, the photobiological risk (part of safety) was evaluated according to the most complete standard, the EN 62471:2008. It is worth repeating here that the used source has been classified in RG1 (risk group 1) because of blue light component, UV and IR emissions are not relevant and no labelling is required.

For what concern the ElectroMagnetic Compatibility,

- Radio disturbance: EN 55015:2006 + A1:2007 + A2:2009
- Immunity: EN 61547:2009
- Harmonic current emissions: EN 61000-3-2:2006 + A1:2009 + A2:2009
- Voltage changes, voltage fluctuations and flicker: EN 61000-3-3:2008

It is not of interest to report here the entirety of evaluation, testing, modifications or definitions relative to the design of the light source in order to comply with the huge quantity of technical requirements. This is, somehow, a standard work that has been done for the majority by the suppliers, even if conducted by me. However, the integrated light source should undergo tests as well, and, as already described, the source is a part of a recessed luminaire, ideal for drop ceilings.

At the same time, the obtained solution requires that the heat produced is removed by air circulation. In the ideal case the fan should work with free air circulation and an adequate ambient temperature, typically below 25 °C.

Stressing the use, tests have been done by me aiming at the definition of minimum air volume needed in order to guarantee a sufficient power dissipation. Beyond the physical definition of the problem, that would require exact edge conditions, the real test is performed by means of an insulating substrate (wood) that enclose the Equipment Under Test (EUT) and avoid air exchange with the external world, where the heat dispersion is obtained just by the temperature variation across the entire surface of the cited material.

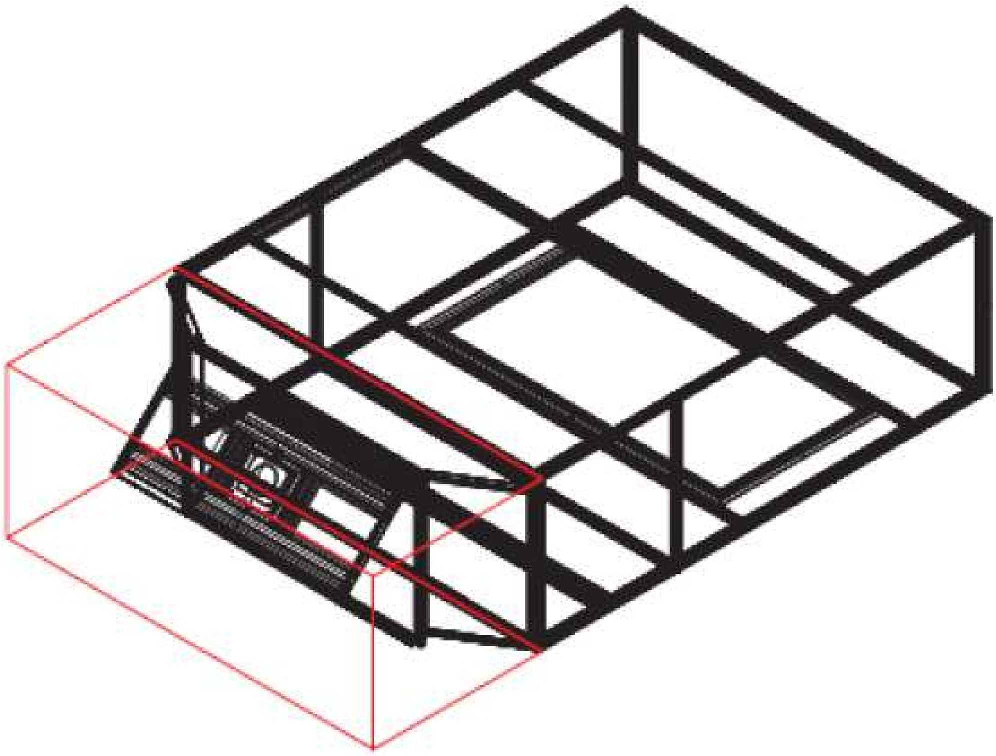


Figure 81 - Overview of the product

Trying to minimize the required air volume (highlighted in red in Figure 81), in order to have the easier requirements for working, the obtained value is equal to 1.5 cubic meters. It is worth noting that the same volume might be distributed nearby the entire luminaire, which is in fact a typical condition happening because of mechanical requirements.

Technical construction file

In Figure 82 is reported a front page of one of the test report produced by an accredited test laboratory. All these report are collected in what is called "Technical Construction File" that also contains drawings and design consideration for the product itself as well as datasheet and declaration of conformity of every component. This necessary collection should be conserved by the manufacturer and shown, under proper request, to the authorities. Not every page of this file is public; here below follows a short extract of some test result. It is worth noting that all this documentation is strictly necessary and is part of a complete light source design. I directly coordinated this action as this is a complementary part of the work on the light source. In the captions there is a short description for every Figure.

TEST REPORT	
EN 60598-2-2 Luminaires	
Part 2: Particular requirements **Section Two – Recessed luminaires**	
Report	
Reference No. .... :	SAFTR_140996-1
Compiled by (+ signature) .... :	Firmato digitalmente da [redacted]
Approved by (+ signature) .... :	Firmato digitalmente da [redacted]
Date of issue.. :	2014-12-11
Testing laboratory	
Name .... :	Prima Ricerca & Sviluppo s.r.l.
Address.. :	via Campagna, 92 - 22020 Faloppio fraz. Gaggino (Co) - Italy
Testing location .... :	as above
Applicant	
Name .... :	CoeLux s.r.l.
Address.. :	Via Cavour, 2 22074 Lomazzo – Como - Italy
.... :	Tel +39 02 36714394
Test specification	
Standard .... :	EN 60598-2-2: 2012 used in conjunction with EN 60598-1: 2008 + A11: 2009
Other standards.................................. :	EN 62031:2008 EN 61347-2-13: 2006 used in conjunction with EN 61347-1: 2008 + A1: 2011
Test specification	
Type of test object .... :	Recessed luminaire
Rating and principal characteristics. :	230 Vac ; 50/60Hz ; 400 W ; IP20
Trade mark (If any)............................ :	CoeLux

Figure 82 - Test report front page

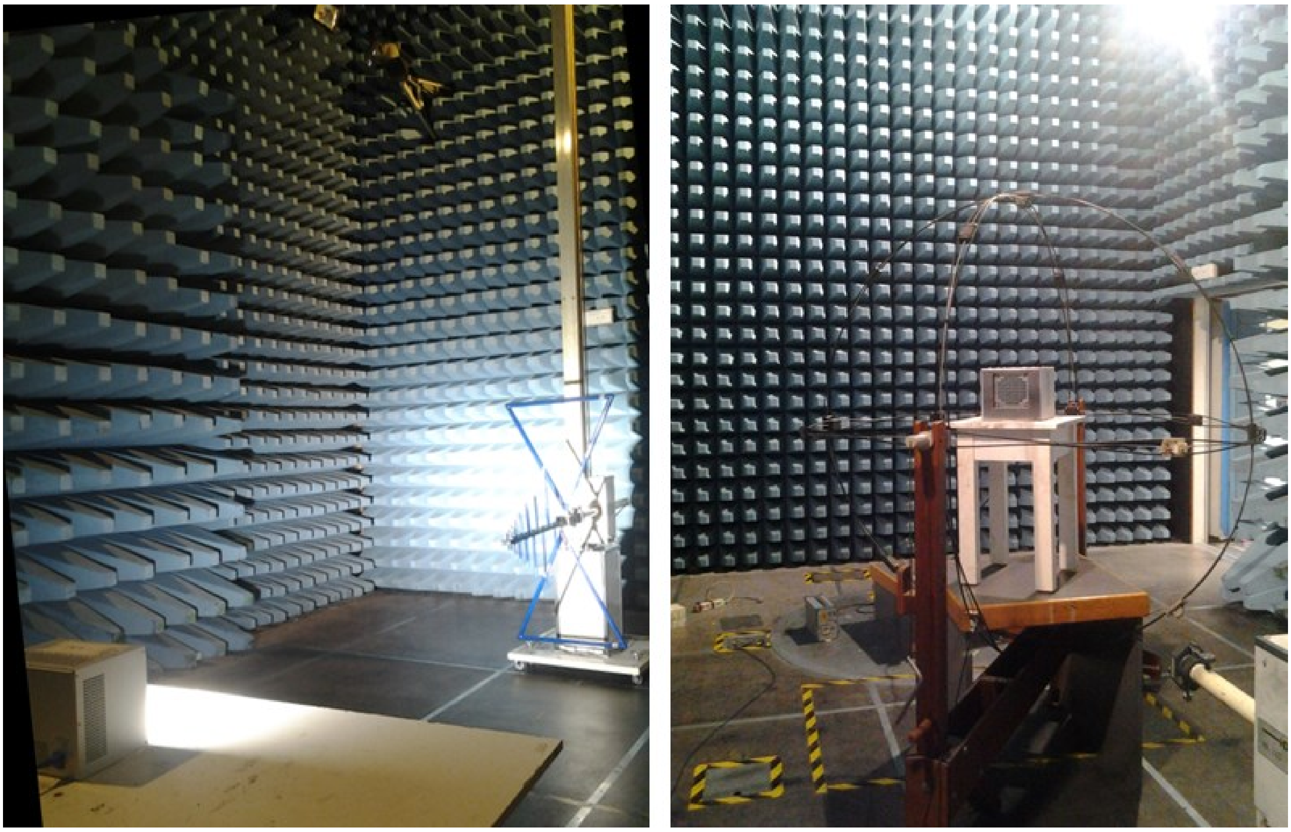


Figure 83 - Light source under test in an anechoic room. In these two different setting can be recognized two different antenna useful for measuring different ranges of frequencies

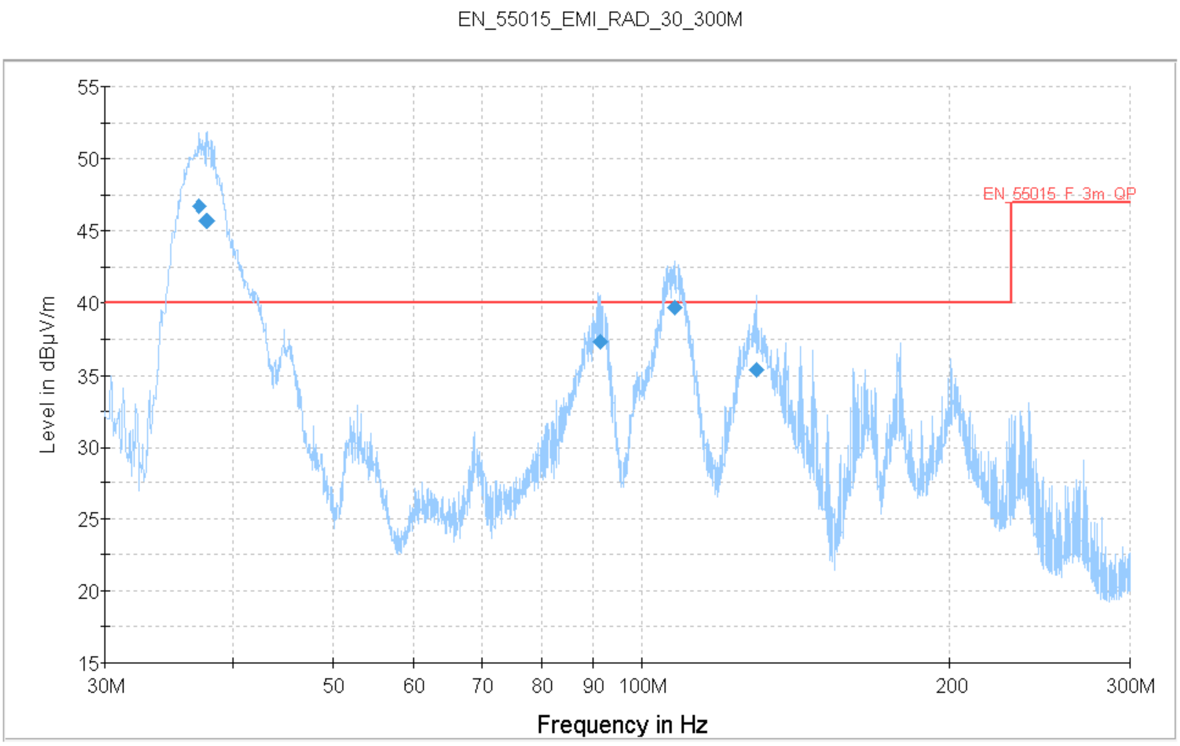


Figure 84 - Emitted electromagnetic radiation in the "high" part of the explored spectrum.
In this case the blue points (quasi-peak emission) are somewhere over the limits given by the standard.
Some modifications are needed.

EN_55015_EMI_RAD_30_300M

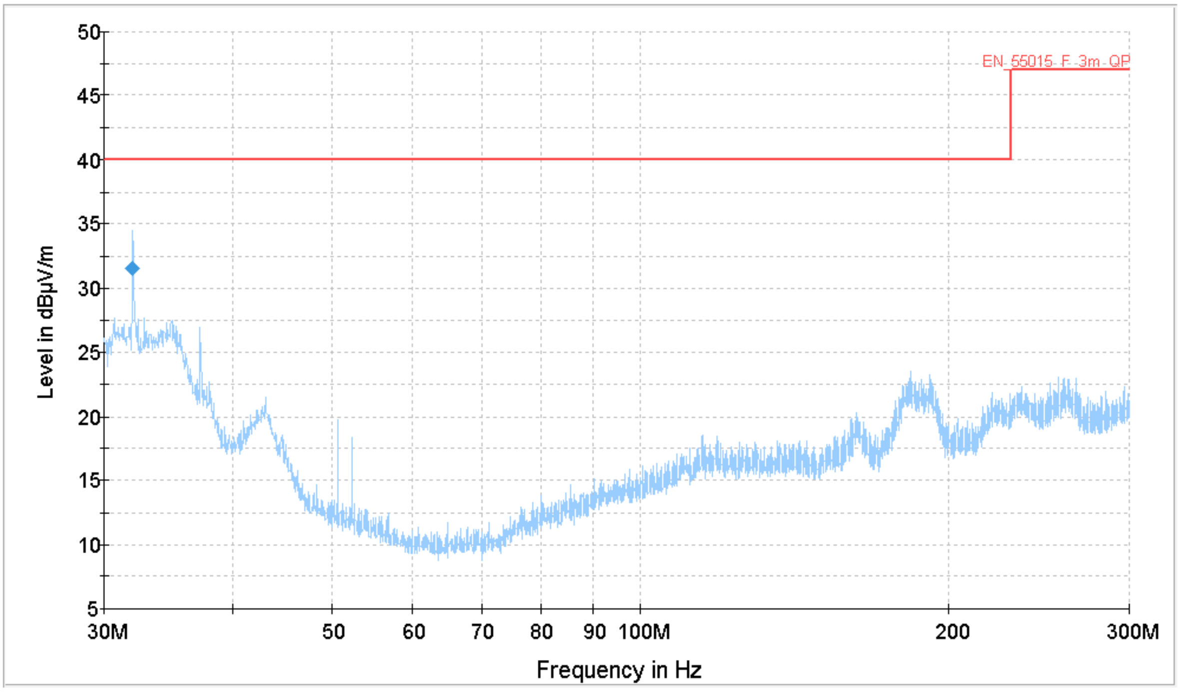


Figure 85 - Same as Figure before, where modifications have been implemented. Test result: Pass

EN_55015_EMI_COND_MAINS

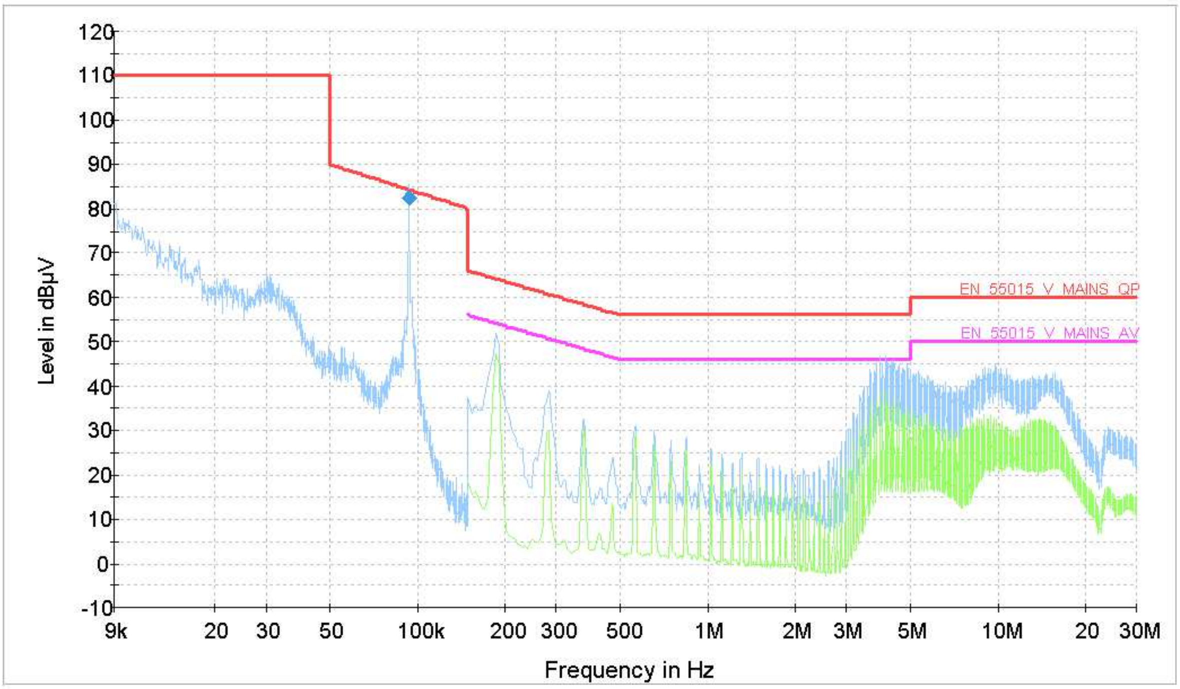


Figure 86 - Conducted radiation (within the main power cable).
Two limits are present, both for Quasi-Peak emission and for Average emission.
It is evident the presence of a switching frequency with every harmonic
repeated over the spectrum at higher frequencies.

Finally, it should be noted that an additional version of the light source has been created at the same time in order to comply with a different standard. Finally, the UL mark has been obtained, opening the possibility to sell such a product in North America. Beyond the fact that such a certification required additional tests, the fulfillment of the entirety of UL1598 standard requirements has been obtained only setting a number of modifications that were not foreseen. These were mainly on the electrical side, involving finally also the mechanical design. I coordinated also this action in strict cooperation with CoeLux Srl and all the involved suppliers.

A complementary feature: the Moon

1 - Introduction

In this chapter I describe an additional part, developed after the completion of the bright light source, the artificial Moon.

In the previous part of this work, the importance of the real sunlight has been reported: it is the preferred light source for humans, and it plays a role in life regulation (biological clock). On the other hand, during the night, the delicate moonlight visibly characterizes the otherwise dark scenario: the moon face shining in the sky immediately pictures the well-known celestial body that is associated with the Earth's nights.

As easily understandable, this feature completes the functionality of the source developed, such that the same becomes adequate for creating the light source alternate to the sun, allowing the nighttime scenery to be created by the same window (product). As a matter of facts, the possibility to create the natural counterpart of the daylight became a question after the creation of the bright light source, as a desired evolution.

Then, the features expected comprised both:

- to create the infinite space perception even with low luminance level (and power consumption)
- to create also non visual effects complementary to the Sun.

The Moon feature allows CoeLux products to be used all day long according to circadian rhythms (because the system is able to replicate both scenarios of day and nighttime) in a perfect quality integration, creating an additional intimate scenario.

In the present chapter the technical work required for the creation of a device able to realize the desired visual appearance is described; this part of the work, complementary to the main argument described in the previous chapters, was conducted by me in the company framework. Moreover, this chapter reports the invention I realized, which CoeLux Srl filed as an international patent application.

Main drivers of the work

Abiding by the company quality standard, the Moon product should be realistic and able to inspire the same effects as the real one. Thus, recalling one of the basic principles of CoeLux, the Moon should also be perceived at an infinite distance. For this purpose, the easiest way of proceeding with this improvement of the product is clearly to maintain the same physical light source and the product structure, since these are exactly designed having similar aims. In this way, the number of additional components might also be minimized, thus allowing for the upgrade of the artificial window (from "only Sun" to "Sun-Moon") targeting the minimum cost.

The quantity of light entering the room and the maintained perceived infinite space beyond the window are targeted to be realistic when experiencing both the day and night states of CoeLux. In this sense, it is fundamental to note that any modification of the system needed to recreate the Moon should not affect the quality of the Sun.

On the other hand, it should be immediately noted that the luminance difference between the Sun and the Moon is huge (1.6 10^9 cd/m^2 vs 2.5 10^3 cd/m^2 (Palladino, 2002)). This characteristic is anything but obvious from a lighting point of view: such a difference, given the comparable angular dimension of the sources, produces a significant difference also in illuminance, in principle creating incommensurable scenarios (i.e. not a simple variation, but a completely new status).

Finally, the Rayleigh scattering should be also considered. As many painters noticed when representing a nighttime scenario, the Moon sky is not dark and black, but shows a perceivable bluish luminance too. Therefore, the realistic reproduction of this effect would contribute to the final result of this work. Notably, thanks to the dedicated panel, this mechanism is already present in the product, enabling the atmosphere effect, which determines the luminosity and the color of the sky, not only under the Sun in day time, but also under full Moon illumination during the night. However, in the CoeLux system a significant unbalancing of sky and sun luminance is present, operated by the panel itself. This is not relevant when the system works as a simulation of daytime, while can be critic approaching the present situation. Indeed, the artificial Sun is set for showing a luminance of some 10^6 cd/m^2, and the sky luminance is near to 10^3 cd/m^2. These values differ from the reality mainly because of the ratio: CoeLux system shows 3 order of magnitude, while in nature the same ratio results in 6 order of magnitude. On the other hand, the angular dimension of the artificial sun is larger, thus for what concerns the illuminance levels the difference is diminished. Notably, the difference in luminance ratios is not perceived as relevant by the observer when simulating daytime, because the Sun is glaring and saturates cones of the eye.

However, this effect might critically vary at much lower light levels, as it should be for the Moon state. Therefore it is not obvious whether it is possibile to recreate a convincing nighttime scenario, because of the presence of the sky panel, which works for daytime simulation but might be critical for the Moon state.

2 - Work done

In this chapter, for the sake of clarity, I limit the description to the actions I have done to implement the different layouts I have investigated; while results are shown and interpreted in the following chapters.

a) Dimming the sun

The quantity of light produced by the source largely exceed what is required: in the Sun mode, the projector shows 5.7 10^6 cd/m^2 (Figure 68), then it should be scaled approximately by a factor of 10^3 for a Moon mode (assuming the reference value cited above equal to 2.5 10^3 cd/m^2). At the same time, it should be noted that the realized design of the projector, exposed in the previous chapters, is based on the fact that a high flux density is needed while optimizing the efficiency. Beyond the optical component, also the other parts have been optimized: from a technical point of view, the electronic components chosen and the electrical driving strategy are configured to excellently supply a significant amount of current to each LED (i.e. 400-500 mA per LED). In the present application, however, the purpose is to use the cited projector for a low luminance scene. Clearly it is not feasible to let the excess of light amount to be absorbed by the mask (overheating would be significant) and therefore a reduction of the electrical current value is desirable.

Beyond the well known side effects of flickering which are often related to pulsed current (Shepherd, 2010), the only applicable solution in the present case was a "PWM" (PWM – Pulse Width Modulation) approach, since no other solution was compatible when developing the moon prototype. Technically, this operating condition supplies a controlled pulsed current on fast time cycles: in the easiest approach it maintains the current value of the pulse equal to the previous condition, and switches off the LEDs for a fraction of second between pulses. The obtained result is a rapidly pulsed flux, of which the mean value should equate the desired one. The frequency shall be higher than what can be noticed by humans.

As for the work of my thesis, it was sufficient to implement the PWM solution paying attention to avoid the introduction of undesired effects, such as a flickering visible by naked eye. After the conclusion of my thesis work, however, the engineering team in CoeLux decided to implement additional electronic features, such as the dynamic control of the pulse height, for the scope of totally avoid undesired effects of PWM.

b) The structured surface of the light source

Figure 87 shows the previously described "bright light source" when dimmed at 1/256 current. This image well reflects the appearance of the light source when operated in order to obtain a mean luminance value similar to that of the real Moon (mean operated across the entire visible surface which emits light). No difference in appearance is evident for a significant range of luminance investigated near the cited value: at least for current values between 30% and 0.05% of the "sun mode". This current range is significant for the present work and accounts also for the different optimization that can be necessary and their eventual effect also on the final quantity of light.

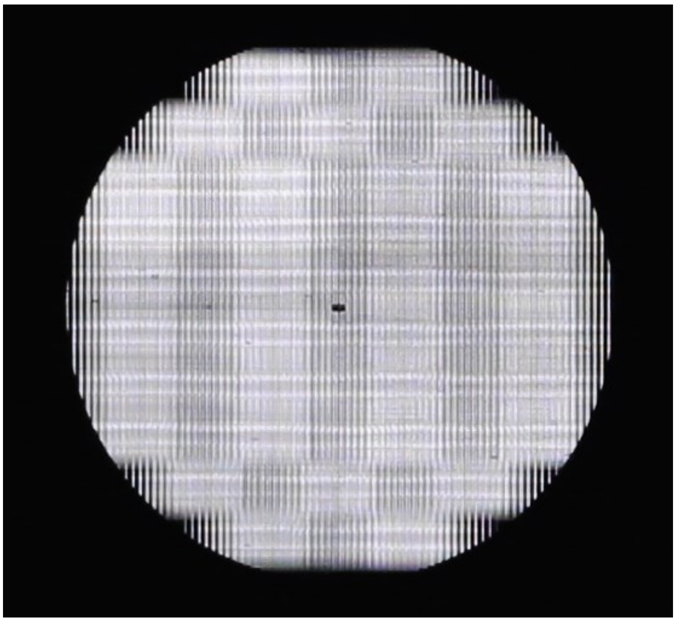


Figure 87 - The bright light source appearance when dimmed

One can easily recognize that approaching this range of luminance a well defined structure becomes visible. It is worth noting here that this effect is completely avoided when the source acts as the sun (with much higher luminance), thanks to the glaring effect, which practically prevents the observer to notice such structures.

This perceptual difference is fundamental, because when looking at the source dimmed, an observer would not perceive the desired depth perception. As a matter of facts, when looking at such a low brightness light source, the observer recognizes an artificial structure behind the window. Practically, the observer's eye accurately focuses on the grids shown in

Figure 87 thus allowing for an evaluation of the real distance – which is not infinity but approximately 5 m.

Specifically, regular modulations occur, showing "high frequency" and "low frequencies" structures. In what follows, these terms indicate the fine details and the smooth modulations, both creating vertical gray lines. Also, two other features are notable in the same image, namely the black dot in the center and the structured perimeter (visibly not circular). Of course, all these are correlated to the underlying optical structure of the light source, originated by its optical components.

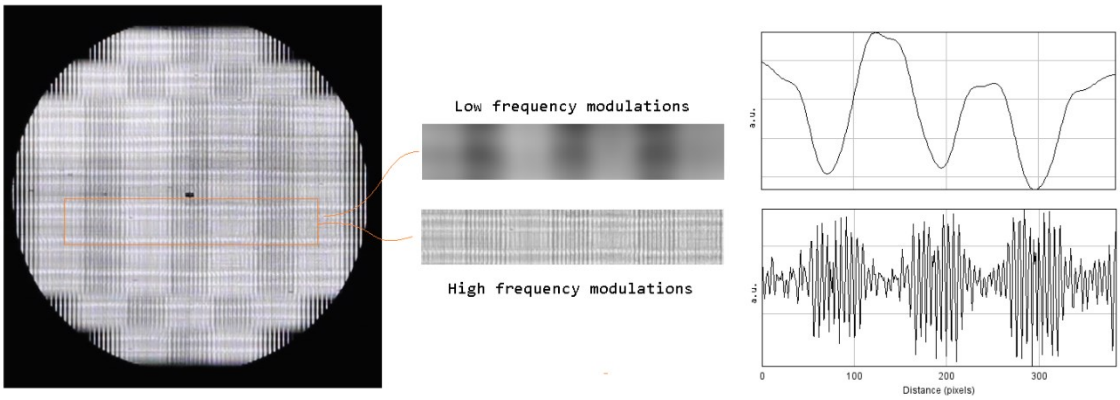


Figure 88 - Spatial brightness modulations of the light source aperture.
From the previous image a smaller part is roughly analyzed: using two simple bandpass filters, the contributions of low and high frequency modulations are highlighted.
Graphs report pixel values, 1 cm on the real object corresponds to 38,4 pixels in the picture

In Figure 88 the image of the dimmed light source is analyzed: for a length of 10 cm (highlighted in the centre) the modulation of the light intensity is plotted on the right, roughly splitting the contributions at low and high frequencies. This structure is related to the optical design of the source itself:

- low frequency modulations can be easily related to the reflector geometry: central and peripheral zones of the exit aperture of CPCs show different luminances
- high frequency modulations relate to the lenses' pitch of the fly's eye integrator; the exact luminance variations on this scale reflect both the uneven illumination produced by the CPCs and the angular distribution of the light passing through each small lens (analysis not reported here)

The horizontal dimensions of these components are 3.4 cm and 1.65 mm respectively, which fits the length of the two modulations.

However, to change the optics to avoid this problem is not doable, as these are designed for the main scope of the product, and effectively work in recreating the sun appearance. Clearly, such a structured image is unsuitable when trying to recreate a moon image.

Therefore the aim is that the observer should not realize that the light emitting area is associated with an artificial light source.

The selected approach was then to hide the structures by interposing a low angle light diffuser between the projector and the observer, practically preventing the latter to see the details of the object. Such effect, which can be described by a Gaussian convolution, depends on the properties of the diffuser, the dimension of the structures and the distance between these.

In the present case, the most relevant modulation which should be considered is the "low frequency" modulation because is the largest one in appearance. Figure 89 shows the profile of the modulation, where the relative luminance is plotted. This image is obtained applying a bandpass filter in ImageJ, filtering structures smaller than 20 pixel, which for that image equals 0.52 cm. The significant variation of 8-9% should then be reduced and not be visible by the observer.

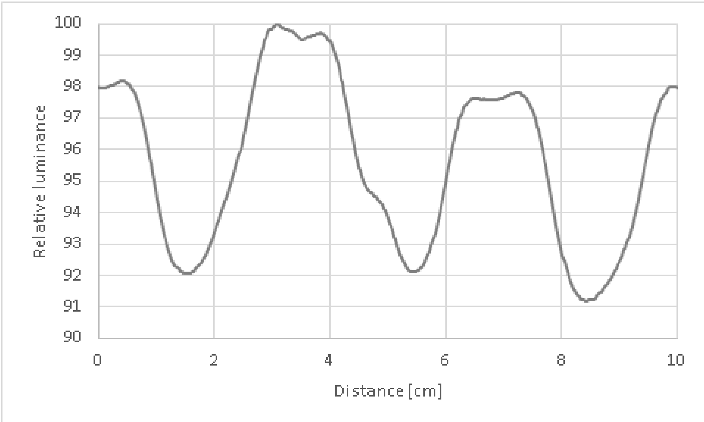


Figure 89 – Relative luminance of the "low frequency" modulation

c) First case: diffuser at the window level

The first and easiest strategy to deal with the described issue was to insert the light diffuser just before the Rayleigh panel, exactly above it, i.e. at the window level, covering its entire surface. As depicted in Figure 14, this means that the distance between the diffuser and the source is equal to 4 m. Then, considering the dimensions of the unwanted structures visible in Figure 89, it results that a diffuser having a very limited diffusing power can be sufficient to hide the unwanted structures, as the subtended angle is less than half a degree. (Equation 11).

$$tg(\frac{0.034\ m}{4\ m}) = 0.49\ deg$$

Equation 11

The diffuser selected is a technical glass from “Berliner Glas” (GW80 - Precision Structured Glass Surface) which is a worked transparent glass. The diffusion of light is obtained introducing a fine roughness of the surface (R_z=1.3 um)[11]. However, the producer do not characterize the angle of diffusion, and this was measured in CoeLux laboratory, obtaining a FWHM equal to 0.88 ± 0.02 deg.

As shown below, such a diffuser is sufficient to hide the structure, as requested, and being positioned at the window level acts on the appearance of the product creating the effect of having a window with a satin glass.

d) Second case: the mask

In the second case, the unwanted structure was hidden following a different approach.

It is clear that a regular “artificial” structure can not create a realistic effect, both because of its shape (i.e. a grid in the case in Figure 87) which does not recall in our mind any real situation, and because the eye's capability to directly focus on it. On the other hand, it has been noted that the real Moon shows a very structured surface, that is the real moon face, which is constituted by large bright portions and less-bright area which are the "lunar maria”.

Then, the second approach was to recreate the familiar appearance of the moon by means of a gray filter reproducing a picture of the moon (Figure 90). Notably, this approach introduces a higher complexity with respect to the previous one: such filter should be inserted each time the mode of the system is switched from "Sun" to "Moon", whereas the first approach only required to dim the light source.

The real image of the moon was printed on a transparent 2 mm thick polycarbonate sheet. In order to obtain a significant absorbing power where required, i.e. in the most dark area of the moon face and outside the circular area of the moon face, the ink properties were optimized with the help of the supplier.

[11] Technical datasheet is available on the website of the producer: https://www.technical-glass.com/sites/bg3-tg-de.berlinerglas.de/files/images/downloads/data-sheets/pdf-english/technical-data_bg-nonflex.pdf

Figure 90 - Real picture of the Moon used

However, as clearly visible in the calculated image (obtained by ImageJ), shown in Figure 91, this would be not sufficient to hide the unwanted periodical structures. In particular, both low frequency and high frequency modulations remain visible, as well as the black dot in the center.

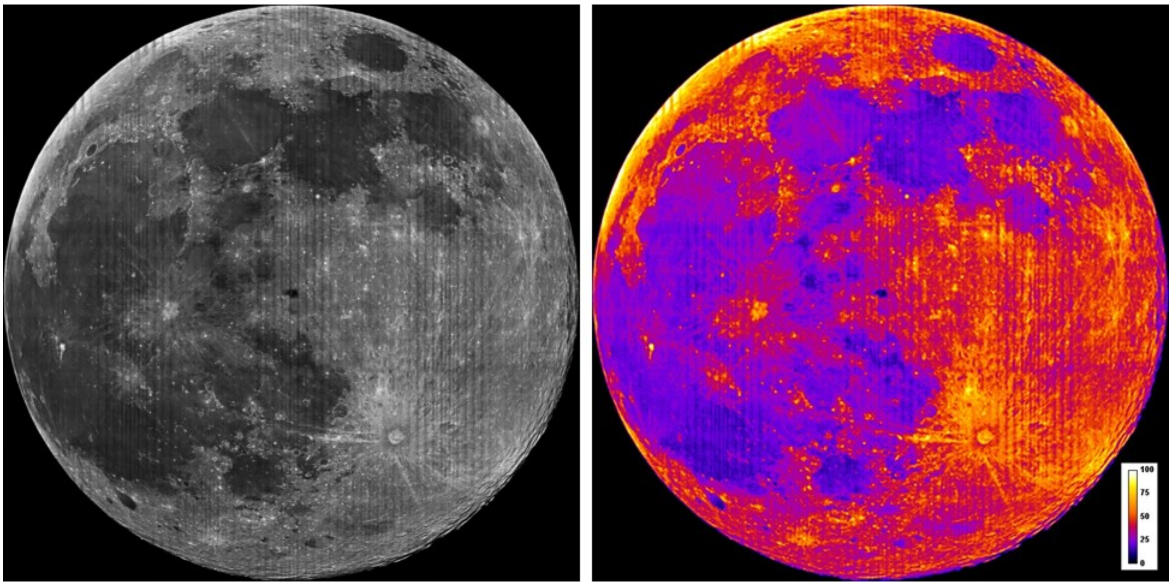


Figure 91 - The simulated appearance of the light projector as seen through the gray filter reproducing the Moon face. Gray values (left) and false colors (right)

Then, also in this second case a light diffuser can improve the appearance, when placed near the source itself, thus requiring a larger diffusing angle.

Moreover, the diffuser in this design is placed well behind the window, and therefore, in this case, another requirement should be considered. While the projector optical design minimizes the amount of light out of the target, the diffuser, which is now necessary, might provide unwanted light on some internal surface. As exposed above to the artificial sun (chapter "Preliminary requirements"), the product structure requires the projector to produce a well-defined light beam, i.e. outside the target (that was 30° x 10° beam) it was requested to have no light.

The best diffuser was found by means of a trial and error process, considering also the positioning distance from the projector aperture. In fact, the maximum allowed distance of the diffuser from the light source was fixed to 5 cm. This distance, suggested by the engineers in CoeLux, allows for a sufficiently compact design of the complete light source which should comprise the additional moon feature.

The final diffuser selected is a plastic diffuser "Fasara" by the company 3M, showing an almost Gaussian diffusing profile with FWHM equal to 15°. It is worth to note that such blurring power within the allowed distance can not produce a completely uniform luminance. In fact, the convolved distance result in 1.34 cm, which is much less than the undesired luminance modulation present on the projector surface. This effect is clearly visible in Figure 92.

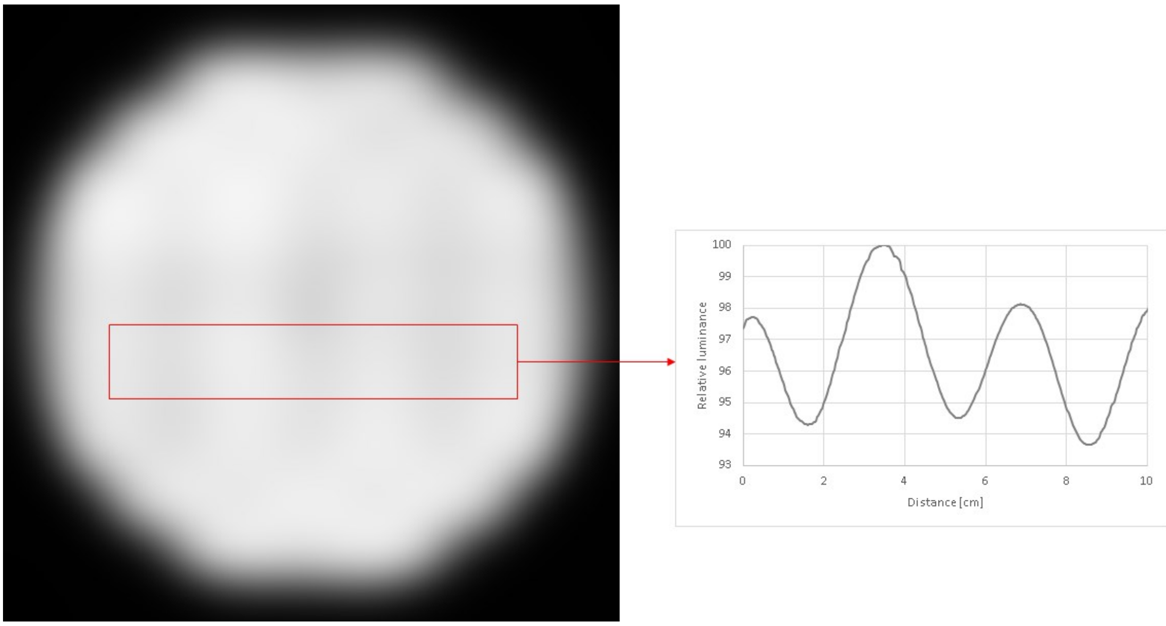


Figure 92 - Appearance of the light projector when seen through the Fasara diffuser positioned 5 cm away from the light aperture

However, the Fasara filter positioned at a distance of 5 cm is by far sufficient to cancel the high frequency modulation that was visible in Figure 91. At the same time, the luminance variation on the low frequency is diminished to around 6%.

Beyond the effect on geometrical properties, it was noted that both the mask and the diffuser also act on the spectral properties of the light. In fact, these plastic components both slightly absorb some blue light, at the end producing a yellow source.

The real Moon as seen from the Earth actually is yellower than the (real) Sun, being the CCT of the Moon between 3500 K and 4100 K and of the Sun between 4500 and 5300 K in similar condition (first of all the altitude). Unfortunately, the color shift due to the plastic components was larger than the desired difference. As a consequence of this, also a blue filter was included, easily selected from the product catalog by the company “LEE filters”. The integration of the blue filter #203 allowed for the color correction from 3100 K to 3600 K of the moon surface when seen after the CoeLux diffusing panel, giving the perception of a realistic moon.

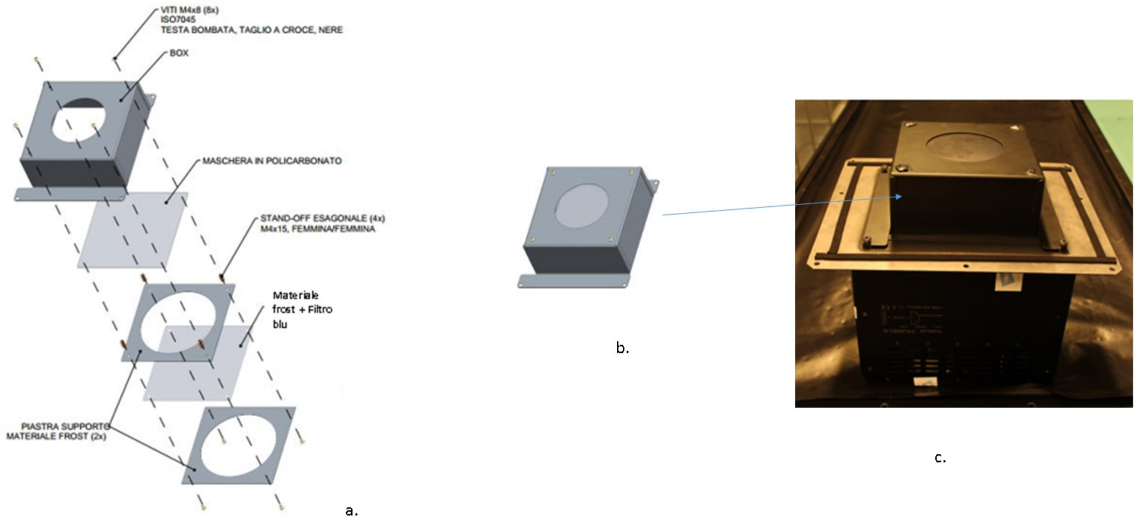


Figure 93 – Moon mask assembled components
The gray steel plate visible in (c.) is needed for the final assembly on the complete system

In Figure 93 the assembly of this component is shown: the Fasara filter is positioned downstream the light projector at 5 cm from the light aperture, slightly separated from the polycarbonate plate where the moon face is printed. Both these components are contained in a black steel box, in order to block any unwanted light scattered from the diffuser. On the left (a.) components (mask, diffuser and color filter) and the needed mechanical components are separately visible, while on the right (c.) the projector is shown when equipped with the designed additional component “Moon” (b.).

It is worth mentioning that V. Marelli, during his master thesis, contributed in the prototypes realization and characterization, under my supervision.

3 - Results

a) First case results

What has been described as the first case, the insertion of the diffuser at the window level, works according to the requests, creating the effect that is visible in Figure 94.

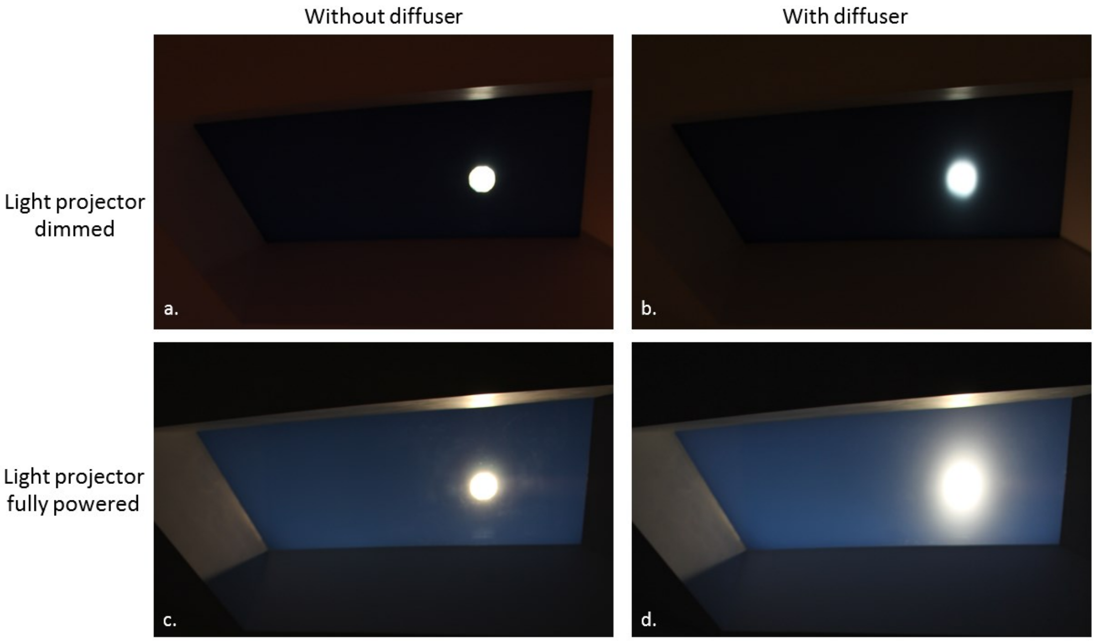


Figure 94 - Comparison of the appearance of the light source when dimmed (a. and b.) or at full power (c. and d.), without the diffuser (a. and c.) or with the diffuser inserted (b. and d.)

The structured surface is hidden and the appearance of the moon is smooth: as visible in Figure 95, the effect of interposing the GW80 diffuser is enough strong to avoid the perception of any structure of the light source.

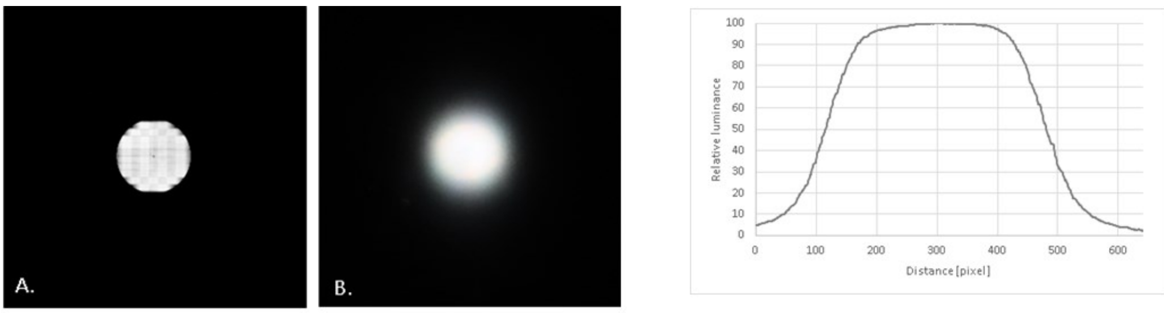


Figure 95 - Zoom on the dimmed light source with or without the diffuser. On the right the horizontal profile of the source is plotted when seen through the GW80 positioned 4 meters away.

Comparing picture A. and picture B. in Figure 95, it is easily understandable that the perception of having a uniform light source is achieved. However, the effect is different from the case of seeing the "Sun" without the diffuser. Rather, it resembles the natural condition of seeing the Moon when a faint haze is present due to thin clouds.

Moreover, once the light projector is fully powered, a natural scenario is visible (part d. of Figure 94). However, this condition is different from what has been exposed in the previous chapter and there are two effects which are characterized here below.

The first consequence is that the shape of the source is affected, because its roundness is not maintained when introducing a tilted diffuser in front of it, this introducing astigmatism. Such solution of introducing a diffuser at the window level, intrinsically brings an elliptic shape of the moon and of the sun, due to the fact that the window is tilted by 45° with respect to the surface of the light projector (reference to Figure 14), thus creating a distortion.

Notably, this effect is present both when the light source is dimmed and when is at full power, however, it is perceived as even more evident in the latter case.

Indeed, even if the observer is glared when the light source is fully powered, both whether the diffuser is present or not, the perception is enough clear to distinguish the shape of the sun. To show this aspect, in Figure 96 two pictures of the different layouts are shown: it is possible to compare the apparent angular dimensions of the two suns for a fixed observer (4.5 meters away from the light source) even if the pictures are saturated, taking as a reference the intermediate value (128/255). On the right, in light brown is shown the profile of the sun without the diffuser, while in gray is the final appearance with the diffuser. As expected, the dimension of the sun is larger when the diffuser is present (2.50 deg vs 1.49 deg on the horizontal axis), but also the shape of the latter is considerably elliptic (3.13 deg on the major axis and 2.50 deg in the minor axis).

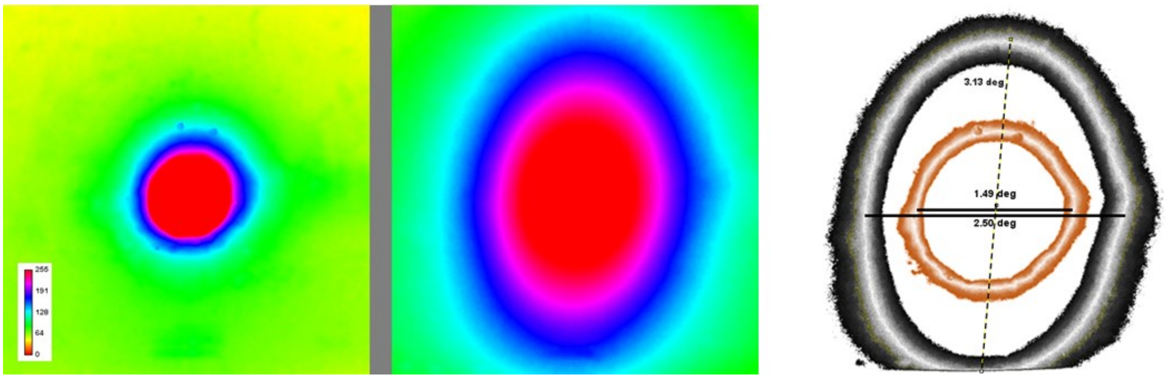


Figure 96 - Pictures taken with the same exposure time (1/2000) and F-stop (f/3.5) to compare the apparent dimension of the light source when fully powered and seen through the GW80 positioned 4 meters away, with the apparent dimension of the light source when no diffuser is interposed.

The second consequence is also visible in Figure 94 and concerns the variation of the properties of the light coming from the sky. In Table 7 the measurements of the luminance and color of the sky are reported for both cases (with and without diffuser) when the light source is fully powered, (see part c. and d. of Figure 94). These measurements have been taken with a spectrophotometer[12] for different angular distance from the sun. Data highlighted in purple are plotted in the following figures and commented.

	No diffuser	*With diffuser*	*No diffuser*		*With diffuser*	
Angular Distance	**Luminance**		**Color**			
[deg]	[Cd/m^2]		x	y	x	y
5	5532	23440	0.354	0.366	0.339	0.355
7.5	4298	14150	0.349	0.365	0.336	0.353
10	1782	2714	0.335	0.347	0.318	0.337
12.5	1212	2196	0.330	0.343	0.317	0.337
15	821	1095	0.320	0.333	0.312	0.332
17.5	732	675	0.316	0.330	0.305	0.324
20	363	448	0.293	0.308	0.294	0.313
22.5	283	385	0.282	0.298	0.287	0.306
25	230	266	0.273	0.288	0.274	0.293
27.5	189	239	0.263	0.279	0.270	0.288
30	161	188	0.252	0.269	0.258	0.276
32.5	139	160	0.245	0.262	0.250	0.269

Table 7 - Measurement of the sky luminance and color when the light source is fully powered

For what concerns the luminance, Figure 97 shows that the sky is more bright when the diffuser is inserted. This is due to the fact that the diffuser scatters in any direction a small portion of the light coming from the source, creating a faint but perceivable background light. Indeed, even if the low-angle scattering is Gaussian-like, as described before, the diffuser redirects some light where it is not needed. This meaning that the decay of the scattering efficacy, when increasing the scattering angle, is not exponential, as for the nominal Gaussian profile. Instead it shows slower decaying tails, this leading to a whitish background that is visible for angles as large as 15 deg, thus affecting the purity of the Rayleigh scattering related to the CoeLux panel.

[12] The spectrophotometer used is the same of the chapter before, the PR-655 by PhotoResearch

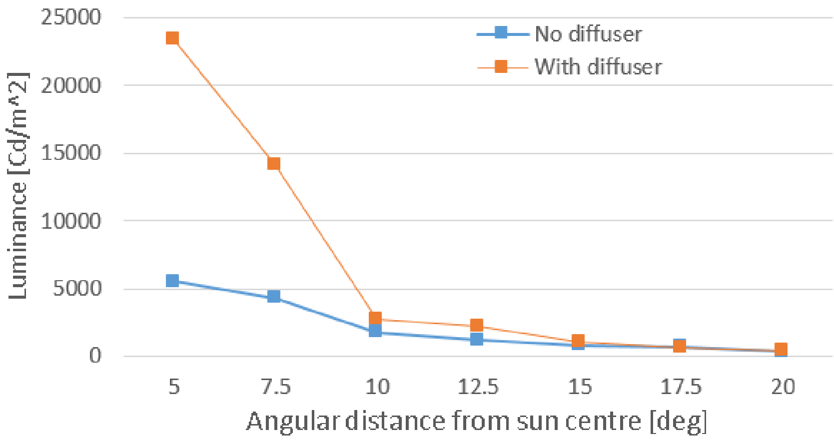


Figure 97 - Luminance of the sky for some angular distance near the sun center

A similar effect impacts the color of Rayleigh scattering: in Figure 98 the colors are plotted for a range of angular distance where the luminance plays a less relevant role. The effect of the diffuser of "whitening" the sky, results in each angular measurement being shifted towards the white point. The difference is clearly visible (average is 2 step MAE).

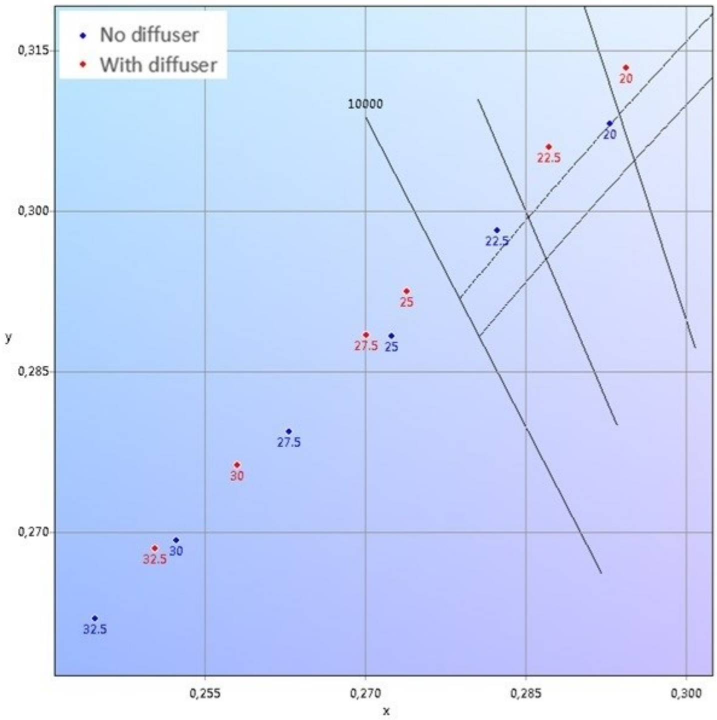


Figure 98 – Color of the sky at large angles when the light source is fully powered.
Measurements are reported on the left: colors are represented in a zoomed portion of the CIE1931(x,y).
Also the final part of the planckian locus and of daylight locus are visible for CCT approaching 10000 K.
Labels near the measurements indicate the angle of scattering measured.
On the right the position of the spectrophotometer for the first measurement is shown.

b) Second case results

The solution using the moon mask is notably related to the opposite approach: to create an image of a non-uniform surface. The second case artificially reproduce the surface of the moon, shown in Figure 100. The overall appearance is natural and shown in Figure 99.

The characteristics of this prototype, mounted on the complete product and observed at 1 meter from the window, are compared with the real Moon visible from the Earth surface and summarized in the following table.

	CoeLux Moon prototype	**Real Moon (typical values)**
CCT [K]	3607	3500 – 4100
Luminance [cd/m^2]	1160	2500
Apparent dimension [°]	1,3	0,5
Illuminance [lux]	0,47	0,15

Table 8 - Artificial and real Moon compared

As apparent, the characteristic of the prototype created resembles those of the real Moon (at least in the order of magnitude) but actually differ from these. However, these were obtained by purpose, as explained in the next paragraph.

The underlying reason for the success of this solution than, is that the observer can not notice the (attenuated) light modulation when this is combined with the image of the moon, produced by the mask, as shown in Figure 100.

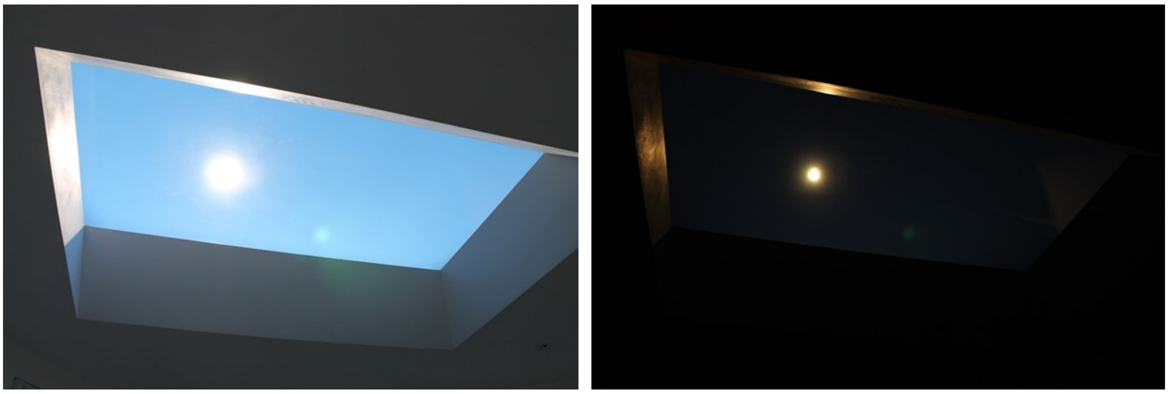


Figure 99 - Comparison of day and night scene of a CoeLux product powered by the same projector, operated as the artificial sun on the left and the artificial moon on the right (different time exposures)

Figure 100 - Artificial moon visible face
In this picture are also visible top and bottom edges reflected
due to the thickness of the CoeLux panel (Fresnel reflection)

4 - Interpretation

The work exposed above in summary refers to three different appearances:

- the projector simply dimmed
- the solution with the diffuser inserted at the window level
- the solution with the mask recreating the moon surface

The first one is the appearance of the projector used to create the sun when dimmed. However, as noted above, this is clearly not acceptable as a realistic reconstruction of the moon because of its structured surface.

For what concerns the other two, both works in creating the requested performance. However, characteristics are very different and here below a short interpretation is reported. Moreover, in order to have a deeper comprehension, these were presented to a group of people in CoeLux asking for their comment and preference, the total number of persons who had seen these solutions being around 20.

Introducing the diffuser at the window level

The result concerning the diffuser at the window level shown above was perceived as overall not very convincing. The failure of this approach, which was the simplest to be implemented, has been interpreted identifying the following key factors.

Firstly, the low angle light diffuser is recognized by the observer, and interpreted simply as a satin window. Thus, the window is not seen as a transparent window, and no element attracts the attention of the observer to interpret the light source behind the aperture as the moon. Moreover, the observer is missing a clear vision towards the outdoor and to really experience such scenario.

Secondly, there is a lack of infinite depth perception. Indeed, the moon was not immediately perceived at an infinite distance as for the case of the sun without the diffuser. Indeed, a key element for the cited perception is the glare, experienced in the sun mode, which prevents the observer from focusing its sight onto the source. Even if the periodic structures are removed, the source is not perceived at an infinite distance, remaining at an "indefinite" distance.

Thirdly, the luminance and illuminance levels were not realistic, i.e. the luminance of the moon, the sky luminance, and the illuminance of the spot created by the moon beam onto the wall were not balanced. For what described in the introduction of this chapter, luminance and illuminance levels differ, as for the Sun state, from the real ones. However, for the Moon state, no saturation occurs in the eye and the different ratio is perceived from the observer. Indeed, the obtained scenario showed a moon luminance similar to the real Moon, but with large sky luminance and wall illuminance. The resulting scene was interpreted by the observers as not realistic.

At the same time, the introduction of the diffuser to hide the light source structure, cause a general depreciation of the system, namely: the shape of the source itself become oval and, at the same time, the sky whitish, and both these effects were perceived very negatively.

Using the moon mask

The solution using the moon mask was perceived, in contrast, as very realistic. All the observers, commented the reproduction as very convincing, even more than the Sun day mode. Moreover, the same appreciation came during the fairs where CoeLux exposed the same device (e.g. Euroluce 2017 and Light+Builiding 2018).

Such result is very surprising, as the reproduced Moon image shows high contrast spatial modulations (but not periodic), which should help the observer in focalizing the light source, then estimating the (finite) distance. The presence of small details was definitely qualified as appreciable by the observers as long as the image created is natural. What dominates in this case is the connection of the perceived scene with the well-known nighttime natural scenario. The brain thus automatically places the moon at the expected distance, i.e. infinite; the same mechanism did not occur in the first case, where the surface of the moon was smooth.

It has been noted that the capability of an observer to evaluate the distance of objects, and therefore the depth of the field of view which constitute a three-dimensional scenery, is based on multiple physiological and psychological mechanisms[13]. As long as the scene does not present an apparent inconsistency, the brain will interpret the physical data (in the described case, the light entering the eye) referring to a known context. In this sense, the more the scene appears realistic, the more the brain is driven to believe that the scene refers exactly to a well-known situation.

It is worth to note that the brain, subconsciously, might even automatically resolve conflicting inputs. In this case, the prime example of solved conflict is the fact that the image of the moon even if not focused by the eye at an infinite distance, can be perceived as the moon being localized far away as in the real world. Also, another solved conflict is related to the luminance and illuminance balancing. Indeed, less attention is paid to these quantities with respect to what described for the first case.

Optimization of the parameters of the moon mask

The artificial Moon is seen as larger than the real one. In fact, this characteristic has been considered, and CoeLux team preferred this condition, saying this gives an enhanced realism of the moon. This might be due to the fact that the Moon plays a significant role in the scene, and it is easier to look at it if the moon's face is a little larger in angular size.

Beyond this, the selected solution comprises also a larger illuminance even with a lower luminance, being caused by the larger size of the perceived image with respect to the real one. Notably, a test was conducted to assess the best luminance value, asking involved subjects their preference about it. It turned out that a higher luminance (e.g. similar to the Moon's one) was perceived as "glaring" or, at least, exaggerated. About this point, it should be considered that the angular size is a significant parameter in the glare perception (see, for example, the definition of the UGR value). Additionally, making the luminance as high as the real one would have caused the illuminance of the moonlight spot (e.g. on the wall) and the luminance of the artificial sky to be by far too large with respect to the natural case (due to the Rayleigh scattering mechanism, the sky luminance is proportional to the moon illuminance on the panel). Moreover, operating at so much low light levels, one should be

[13] Physiological mechanisms are, for example, focusing, binocular convergence and movement parallax perception, which without thinking reveal distances.
Psychological mechanisms, which are relevant also for optical illusions, relate to what the brain is used to see.

aware that human perception of both color and luminance/illuminance levels varies dramatically[14].

The visible result of the prototype described is the creation of a nighttime scenery which differs from the daytime typical reproduction of CoeLux products mainly because the ratio of the quantities of light is larger than 1000.

As for the non visual effects of this light source, this data and the knowledge exposed in the chapters before[15], where the importance of the circadian rhythms has been detailed and some mechanisms of the same have been explored, support the hypothesis that this additional feature enables the device for pleasant and adequate light variations according to the natural rhythms. This has not been demonstrated within the present work, while the scientific research is still in progress, conducted by CoeLux Srl.

5 - Patent

What is exposed above regarding the moon feature, paves the way for introducing the following exposure of the related invention.

In 2016 a patent application has been filed by CoeLux (WO2018108891) to protect the invention related to the moon feature: the patent is still pending, whereas all the claims are marked as compliant with the requests of novelty and inventiveness.

High luminance applications stand in contrast to low luminance applications that need to be considered when imitating, for example, a natural sky scene at night. The concepts described in the patent application are all designed to achieve an enhanced depth perception even for low luminance applications; on the contrary, the largest part of the prior art (when referring to CoeLux patents) is about day-like applications, of which the main application example is described in chapters 1 and 2 of the present work.

The nighttime scenery is conceived as an additional feature of a lighting system which is able to artificially recreate the natural light. In Figure 101 the structure of a system for providing a moon appearance is shown (and labeled as "1"). The beam forming unit, which is labeled "19" in Figure 101, provides a directed light beam of visible light from a circular area in a flat top profile.

[14] A discussion about this point would imply also an evaluation of vision mechanisms involved for this scenario, where for sure both rods and cones play a role (the light levels are those of the mesopic vision).

[15] Reference to "Human Centric Lighting?" at page 15 and "Non visual effects of light" at page 26.

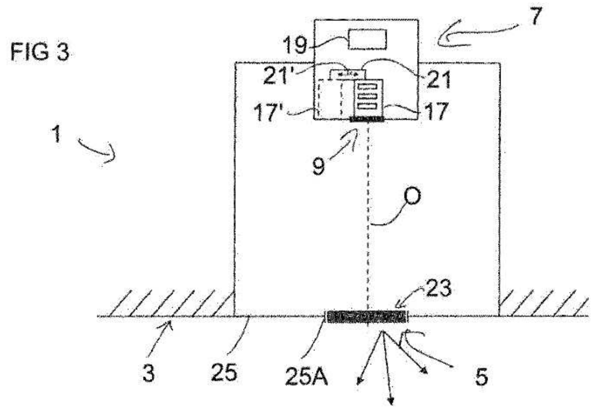


Figure 101 - Structure of the Moon system, from patent application WO2018108891 (Fig.3 there)

Then, the unit "17" (which can be in principle moved in position " 17' "), comprises the transparent panel with a printed surface which is configured to reproduce a realistic image of the moon. In the same unit the diffuser is positioned.

The mask unit is configured to extend across the light beam in the near field and to form a "new" emitting area, obtained modifying the original one by masking. Such emitting area is intended to be the reproduction of the moon surface, i.e. the image of the moon seen by the observer. Then, what is interesting for this application, is that if specific care is taken for the two-dimensional luminous profile at the light emitting area, such as creating the real Moon surface, the observer might perceive the same as a faraway object ("the" faraway object), achieving the desired depth perception.

The mask unit may also comprise a diffusive layer upstream the absorbing element, which is configured to increase the divergence across the direct light beam. The latter may be designed to reduce the visibility of the regular structures present in the light source, which might be caused by the optical components used to create the light beam (as the real case described here).

Then, the moon appearance generating system described in brief comprises a luminous device configured to provide a light emitting area with a two-dimensional luminous flux density profile, which imitates the image of the viewable side of the moon, thereby forming the moon appearance. The same system comprises also all the other necessary components to recreate the day-like light.

In the most efficient case, the image of the moon is reproduced with details that are realistic when considering the resolution of an observer's eye at a reasonable observation distance from the light source, such as in the range from 5 m to 2 m with respect to the window. As an example, considering the fact that 0.07° can be considered as the angular resolution of the human eye, technical sub-structures should have lateral dimensions lesser than 1mm. The luminance of the Moon should be in the range of 0.3 to 3 times the luminance of the real Moon (average 2500 cd/m2 - max 5000 cd/m2) i.e. in the range of 750-15000 cd/m2.

It is worth to note again here that the emitting area will be the more effective the more it is configured to psychologically recall the well-known object "moon," which is far away. This is possible thanks to the luminance profile: starting from the diffusion, and then absorption, of the light from the source.

Then, the "moon" mask unit described includes the diffuser element for removing regular technical structures, and the absorber element for creating natural structures.

The invention in brief

Here below, main themes of the invention are reported, reporting some paragraphs of the patent application description. In addition to what has been exposed above, the optical illusion is described also comprising the presence of the frame, which contains the window, and serves as a reference for the observer who evaluates distances (this frame is labeled as "25" in Figure 101. What follows is equally reported in the patent application WO2018108891.

For reproducing the image of the moon (full or in another phase of the moon cycle), a light source may provide a luminous flux density in the range from about 5 lm/m2 to about 150000 lm/m2, preferably in the range from about 20 lm/m2 to about 50000 lm/m2, more preferably in the range from about 100 lm/m2 to about 15000 lm/m2.

In some embodiments, the image of the moon is reproduced with details that are realistic when considering the resolution of an observer's eye at a standard observation distance from the light source, such as in the range from 5 m to 2 m with respect to the exit aperture. As an example, considering the fact that 0.07° can be considered as the angular resolution of the human eye, technical sub-structures may have a dimension that is less than 1mm.

Moreover, the reproduced image of the moon may be configured in size by a light source having a diameter that is suitable proportioned to resemble the diameter of the real moon at a standard observation distance. In some embodiments, the angle subtended by the primary light emitting area may be less than one degree as for the real moon. In other embodiments, the reproduced image may be configured in size by having that same angle to be larger than one degree, such as up to 5° or 12°.

The capability of an observer to evaluate the distance of objects, and therefore the depth of field of the views that constitute a three-dimensional scenery, is based on multiple physiological and psychological mechanisms. Physiological mechanisms relate, for example, to focusing, binocular convergence, binocular parallax, movement parallax, luminance, size, contrast, aerial perspective, etc. Some mechanisms may gain significance compared to the others according to both the observing conditions (e.g., whether the observer is moving or still, watching with one or two eyes, etc.) as well as the characteristics of the scenery. Those may depend, for example, on whether objects with known size, distance or luminance are present because those may serve as a reference to evaluate how distant the observed element of the scenery is.

Psychological mechanisms are significant for optical illusions and relate to what the brain is used to see. As long as the scene does not present an apparent inconsistency, the brain will interpret the physical data, in this application the light entering the eye, referring to a known situation. In this sense, the more the scene appears realistic, the more the brain is driven to believe the scene refers exactly to a well-known situation.

As a consequence, some peculiar aspects of the scene, even if not present, not well defined or even conflicting, are automatically resolved by the brain subconsciously.

In the present invention, the prime example of solved conflict is the fact that the image of the moon even if not focused by the eye at an infinite distance, is perceived as the moon being localized far away as in the real world.

In particular, the inventor realized that an observer, who is watching a realistic image of the moon through a frame, only with difficulty can estimate correctly how far away the image is. This is in particular the case if the background surrounding the image in the frame structure is uniform. The correct estimation of that distance is not trivial because of the knowledge that the real moon is at an infinite distance.

Further the inventor realized that the frame, which can be easily localized, may act a as reference without affecting the evaluation of the moon distance. The frame distance may be perceived much smaller than the moon distance, thus creating the effect of an aperture through which the real far away moon is visible.

As already said, the real moon’s structures are visible and recognizable. For the aim of recreating a realistic moon imitation, one should take into account that an image of the moon should be similar to the real moon.

To increase the imitations, it will be appreciated that, in some embodiments, the moon image may be imitated by the addition of dark spots/regions on the bright surface, these resembling the presence of the crater-structure on the real moon.

Thus, the moon image may include more than one level of brightness, disposed in a way to mimic those real moon’ structures. It will be understood that the most realistic image of the moon is a reproduction of a photograph of the moon or a similar image.

Facing the world

The present work finds immediate application, not being pure research; here below are reported feedbacks coming from different external sources as well as studies performed on humans in real environment. I acted as a *trait d'union* for the research between the University, the CoeLux company and the other involved actors. Being the reference person for what concern the light source, I have been involved at different levels in each of these valuable works. I supported these where useful, both with respect to the technology (which is abundantly described in this work in the previous chapters) and to the perceptive aspects related to CoeLux. In particular I contributed in the perception tests, which were conducted by M. Canazei, who also collected and analyzed data.

This chapter is significant in this work as it is the prove that the bright light source developed is effective not only from a technical point of view, withstanding the assessments coming from the market and, finally, from the users.

1 - Market feedbacks

The main milestone of the DeepLite project consisted in assessing the applicability of this revolutionary technology, thus bridging the gap between research and development and the market. This was successfully achieved with the realization of eight installations, presenting the CoeLux® technology in different architectural environments and applications sectors - healthcare, retail, office, museum and transportation. The worldwide uproar generated by these installations, supported by numerous events and dissemination activities, have demonstrated that CoeLux® has the full capability of promoting a change in the global lighting market leading to an impressive economic impact.

As an example of the effect produced by the innovation of CoeLux system, it is worth to report here the list contained in the final report of the EU-funded project "Deeplite" which comprise some of the first installations of the cited system:

1. The Ideaworks demonstrator, London, UK - this was the first ever installation of a Coelux® lighting system in a real space. The chosen space was a small underground room that gained new functionalities after the installation of CoeLux. This demonstrator was the first step for CoeLux® to enter the residential and hospitality markets. The demonstrator was inaugurated in September 2014.
2. Humanitas Hospital demonstrator, Milan, Italy - this demonstrator falls in the healthcare applications. A CoeLux® 45 HC lighting system was successfully installed in one of the Gamma Knife radiotherapy rooms, completely blind to the outdoors, where patients spend over 2 hours while their therapy is being administered. The demonstrator was completed in January 2015, staff and patients coming back from the Christmas holidays where astonished by the installation. An event for the presentation of the system to the press and media took place in March 2015.
3. Spazio Spin, Ars et Inventio demonstrator Milan, Italy - a temporary office space rented by companies or privates for focused activities like training, meetings etc. The room in which CoeLux® is installed is located in an old building in the centre of Milan, with two large windows looking on the street. This demonstrator is a successful example of how an office space can benefit from this technology and of how the technology can co-exist with natural daylight. The demonstrator was inaugurated on April 14th, 2015, over 200 people attended the event including Light designers, architects, stakeholders and the press.
4. Boffi Showroom demonstrator, Milan, Italy - is located in the Milan showrooms of the world famous furniture brand Boffi. Here CoeLux® is installed in a setting common to a high end residential building/house. The inauguration took place on April 7th, 2015. The event organized by Boffi saw the participation of over 1500 architects, lighting designer, press agents, and others.
5. Bang & Olufsen, Vilnius, Lithuania – this is the first demonstrator of CoeLux® in a Nordic country. Due to the lack of daylight during the winter season, the Nordic countries represent a very important market for the CoeLux® product. The opening event took place in July 2015.
6. Vilnius International Airport, Vilnius Lithuania – this demonstrator is the first example of a CoeLux® lighting system installed in a large infrastructure space. CoeLux® is positioned in the airport baggage claim area, just before the exit from the terminal. This means that CoeLux is today seen by all passengers arriving at Vilnius Airport. The installation was completed right at the end of the project. An inauguration event with the press and local authorities took place in October 2015.

CoeLux® technology presents a revolution in lighting and the lighting design industry. In this scenario, CoeLux has the full capability of promoting a change in the global lighting market – a market which is historically very conservative with a slow innovation pace often led by cost reduction and energy efficiency optimization rather that breakthrough ideas - which could generate an impressive economic impact. CoeLux is not just part of an environment, but designs and defines the environment generating a new relationship between architectural space and people. In fact, room atmosphere generated by CoeLux can be described as fundamentally different from a standard lighting system. Such an impression was supported by a huge quantities of declaration made by visitors, attendant to the meetings, commenters…

It is worth going in a deeper understanding of the CoeLux effects on humans. In fact, such an effect forewarn regarding positive effects, but an assessment work had to take place: yet there are results that will be discussed, some research is ongoing and more and more evidences are expected to become apparent in the future. Here should be noted that it is of fundamental importance to prove these effects also for what pertains the CoeLux mission described above.

There is plenty of evidences regarding effects of visible light other than image formation, as reported in the previous chapters: consequences are visible in wellbeing as well as in health sector, affecting relax, performances as well as mood, involving, for example, physiology and psychology.

There is an interesting editorial in a dated publication of the New England Journal of Medicine (1970) where Wurtman and Neer wrote regarding "Good light and bad". While they annotated that, at that time, "Essentialy nothing is known about the identity of the portions of the light spectrum that cause the neuroendocrine and metabolic effects of light", they also noted that the public interest for environmental factors affecting the human health was growing (Wurtman & Neer, 1970).

2 - Tests on humans

"The future research should improve the consistency of results, by using both controlled and experimental settings, making so possible to quantify the impact of the setting on the light stimulus, and giving a chance to move from theoretical and experimental to real environments where people live.

The results of all the research activities carried out in the field of the non-visual effect of light are opening a new way of interpreting the role of lighting inside buildings and, in the future, they are destined to change the current approach to lighting design. The concept of artificial lighting as a function of the human activity will be in the future enriched taking into account also the physiological and psychological effects of the luminous stimulation" (Bisegna et al., 2015).

It is worth to note here that the observations made by Bisegna et al. cited above, give an insight to the actual research of the scientific community. Beyond the fact that CoeLux brings a revolutionary innovation in a well-established technical field, methods to study such effects and approaches are defining on the way.

Here are reported few studies which were carried out professionally and actually resulted in amazing conclusions. Nonetheless, an improvement is desirable aiming at confirming results, extending the research and providing a better insight on the potentialities of such a technology. Ethical committees were consulted before starting the studies in order to plainly exclude any undesirable effects.

a) Perception

In the context of the EU-project "SkyCoat" (2012-2015) two studies have been completed about the impact of CoeLux on humans.

At Bartenbach premises, two similar rooms were arranged where people should answer prepared questionnaires in order to evaluate both ambient related and person related effects. The complete set-up is adequately described in the published paper about room related effects (Canazei et al., 2016). It is worth noting here that in the same conditions two different sessions took place, the first one during the winter in 2013 and the second one during the summer in 2014. The second one included the person-related research (Canazei, Pohl, Bliem, Martini, & Weiss, 2017), and also repeated the Room Atmosphere Questionnaire (RAQ) part: the complete sample collected for the latter being so equal, in total, to 200 subjects. Notably, only a small difference has been perceived, showing a smaller significance on RAQ results during the summer test. This has not been deeply investigated, although the hypothesis formulated is that the intrinsically increased daylight exposure of the sample (because of the duration of the day in that season) slightly diminishes the investigated effect. However, the trend was clearly confirmed by the second study and new results were demonstrated, that are here reported, about person-related effects.

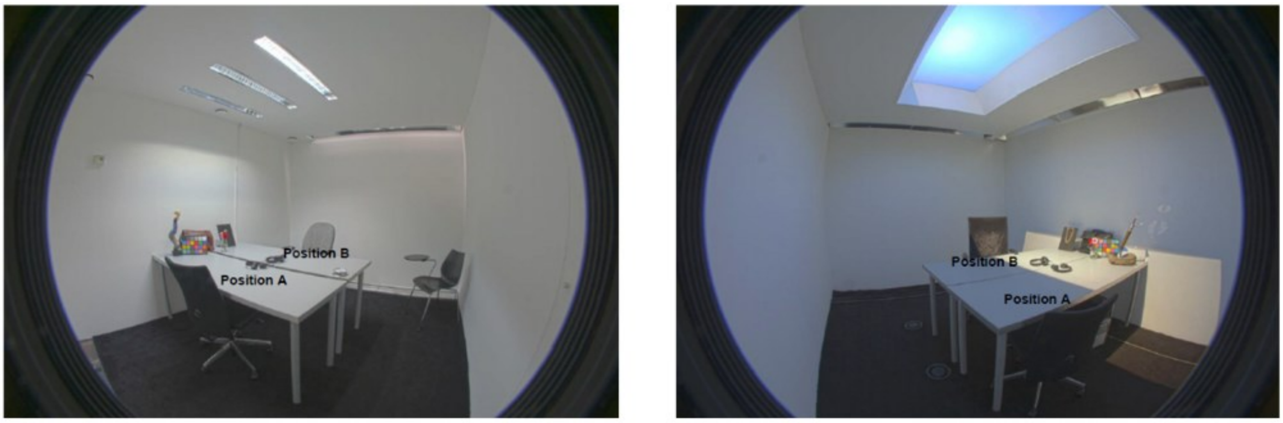


Figure 102 - Pictures of the two rooms: the reference (left) and the room under test (right)

The environment was composed of two rooms of equal dimensions and internal design and furniture, one equipped with standard artificial lighting technologies and the second equipped with a CoeLux® lighting system, which simulates a window on the ceiling. It is worth noting here that the actual light source of this setup is not the same described in this document, because it was not yet finished, and a metal-halide gas discharge lamp was used (while the same is not true for the following test). Notably, good spectral characteristics are of course necessary (achieved both by the source subject of this work and by the lamp used here) as well as the other characteristics described in this work as “requirements” (and obtained in the final prototype). The cited source variation does not affect the results of this chapter. It should be also noted that the studies here reported effectively produced feedbacks in order to settle the source in the final setting as described above.

Room- and illumination-related effects of an artificial skylight

The first study aimed at quantifying the appearance of the CoeLux system and its induced subjective impression of the indoor environment. A synthesis of the procedure used follows here below, as reported in Canazei et al. (Canazei et al., 2016).

Data collection within each mock-up room lasted for 1 hour within which three questionnaires (room lighting- and room atmosphere related questionnaires and connected-to nature questionnaire) were filled out at the beginning and the end of the light exposure. In between subjects executed a neurocognitive test sequence (with results not reported here).

Subjects adapted to the room lighting conditions for 5 minutes at the beginning. Adaptation took place in a seated position either at the fixed seating position in the standard room or at one of the two seating positions in the test room (‘shade’ or ‘sun’). After adaptation, the above-mentioned questionnaires were filled out on a computer screen. To limit visual impairments the screen was located on the desk with solely artificial skylight illumination. Afterwards subjects executed neuropsychological tests for approximately 45 minutes. After a short break of 3 minutes, subjects filled out the three questionnaires again. Since the questionnaires were presented at the beginning and the end of the light exposure, short- and long-term impressions of the room lighting systems could be quantified.

The subjects participated in a randomized controlled trial with a repeated measures cross-over design. Thus, all 100 subjects experienced the situation under the conventional lighting system and in the test room either in the seating position ‘sun’ (n=40) or seating position ‘shade’ (n=60).

The results are shown reporting the statistical mean values as well as the significance (the p-value) which tells the probability of getting the results you did (or more extreme results) given that the null hypothesis is true. Of course, the smaller the p-value the stronger the result is from a statistical point of view: it is the significance value. On the other hand, somewhere is mentioned also the size effect (using Cohen’s *d* or partial eta squared), aimed at quantifying how much strong the effect is in terms of the scores. What it means is clearly depicted in Figure 103 for what concerns the Cohen’s d measure. Its formula is easy: it is defined as the ratio between the difference of the two mean values over the standard deviation of the distribution (Equation 12).

$$d = \frac{\bar{x}_1 - \bar{x}_2}{s}$$

Equation 12 - Cohen's d

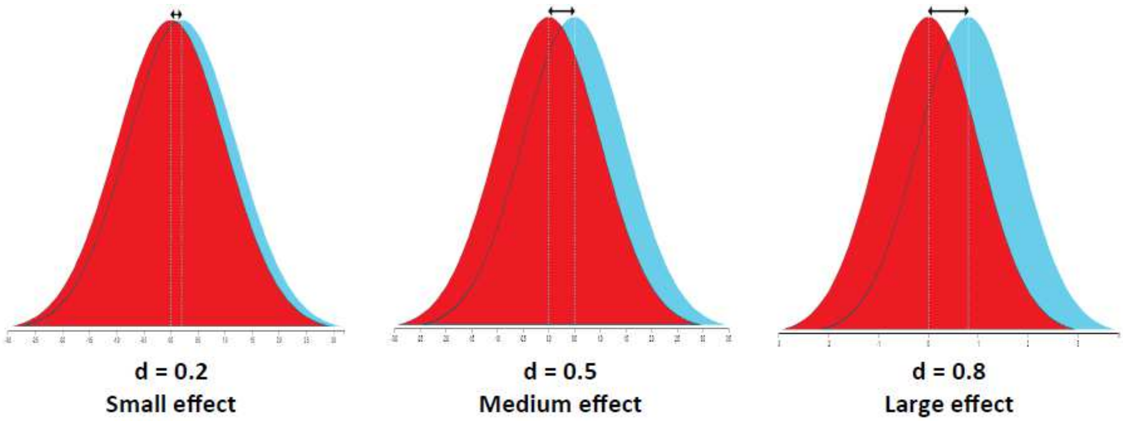


Figure 103 - Cohen's d

The first result is about the item “linked to nature”, that gained the highest difference in the ratings between the two lighting systems. The statistical significance clearly evidenced the difference ($p < 0.001$) together with a large effect size (partial eta squared equal to 0.46). While it was largely expected during the prototypes phase in CoeLux company, the scientific proof has been achieved by this test for the first time, and it is worth noting here. In fact, this and all other items were rated significantly different between the two mock-up rooms although both rooms had no windows and reference to nature was built artificially by means of the CoeLux® system. The specific aim of reconstructing the appearance of a natural lighting is positively achieved, this not mathematically implying any effect on different quantities, sensations or anything else in principle. Of course, similarly to what just explained, expectations on multiple implications are very large, as also described here below. Scientific proofs likely will demonstrate this.

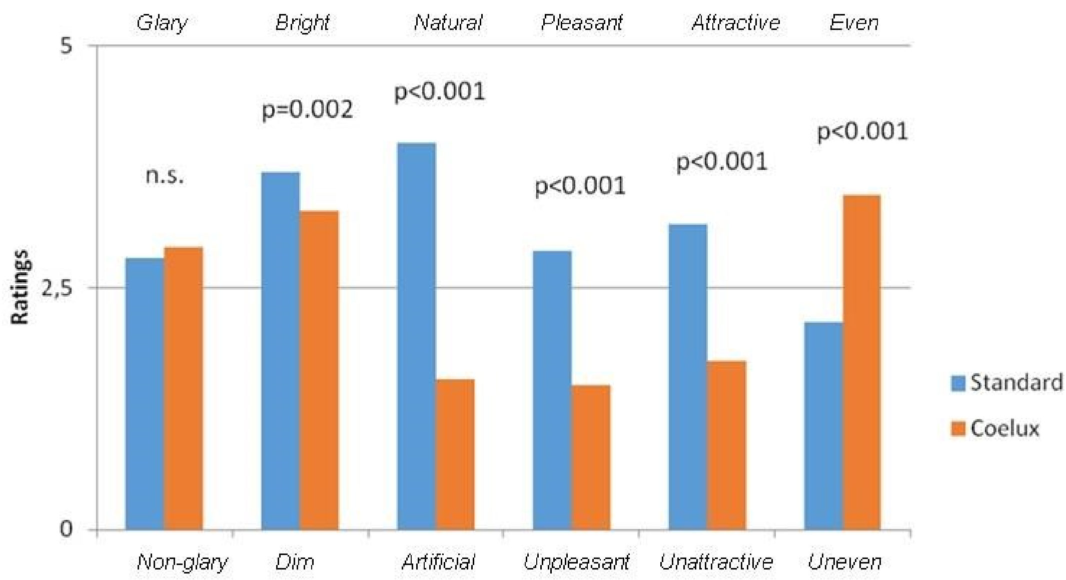


Figure 104 -Results of subjective ratings of the room

The evaluation of room lighting gave the following results, as depicted also in Figure 104: CoeLux room was rated as:

- more pleasant ($p<0.001$). Notably, subjects perceived room lighting more unpleasant in the standard room after 1 hour stay ($p=0.015$) while the same effect was not detected in the test room (in particular see Figure 105)
- more attractive ($p<0.001$)
- more natural ($p<0.001$)
- less even in the test room ($p<0.001$), as easily understandable accounting for the light distribution
- less bright than the standard room ($p=0.018$), even if the actual luminous fluxes were equal

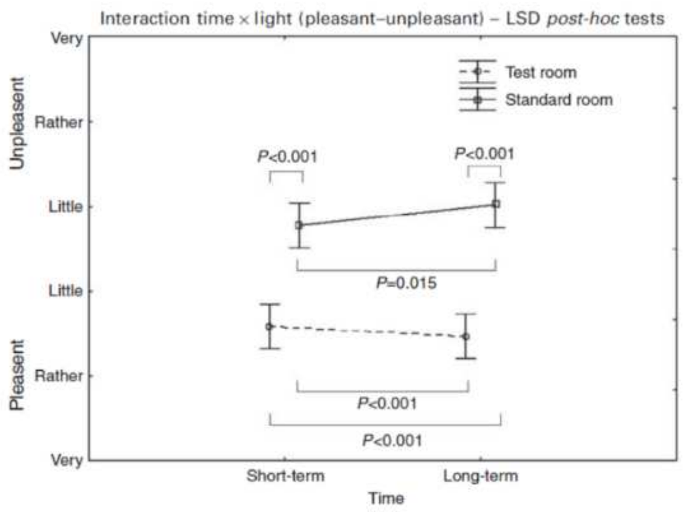


Figure 105 - Perceived pleasantness results

Additionally, the interaction between light and seating position reached significance level (p<0.001) and thus in the seating position shade of the test room, room illumination was perceived less bright than in the other two test conditions. Interestingly, glare ratings did not reach significance level between the test room and the standard room. Moreover, only one interaction (light x seating position) was significant (p=0.011) and thus glare ratings were the same in the standard room and the test room in the seating position sun.

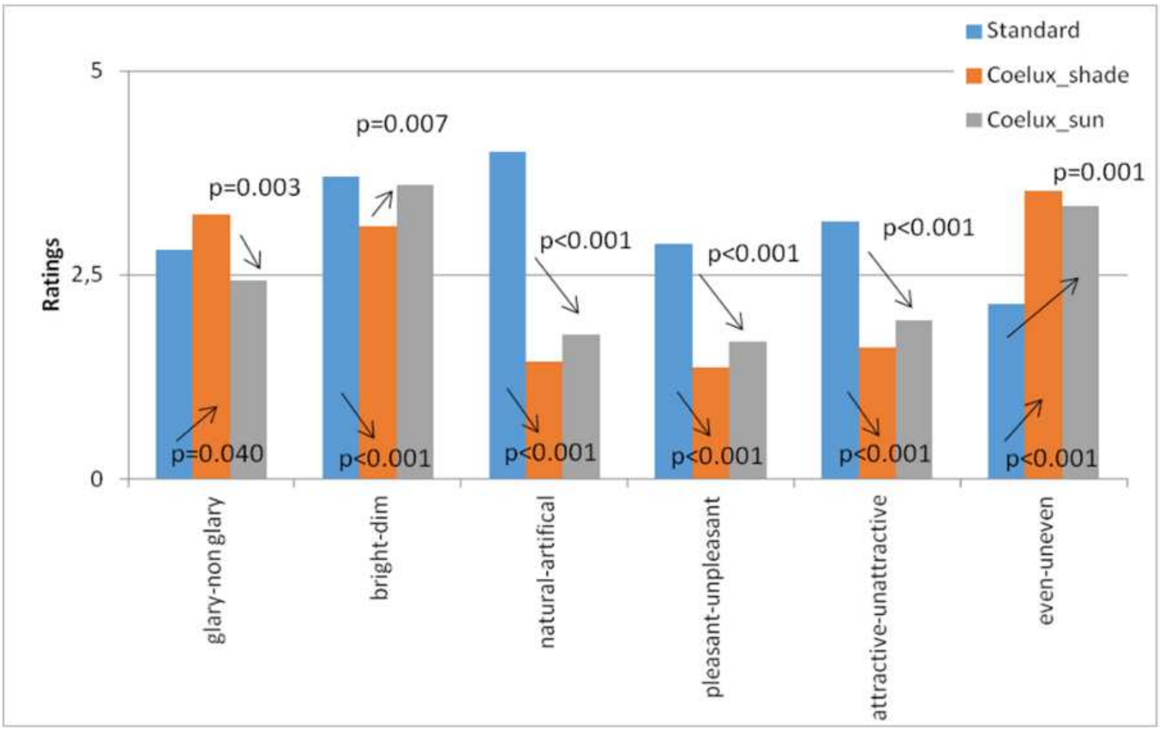


Figure 106 - Results of subjective ratings for different seating positions

All 38 items of the room atmosphere questionnaire were rated highly significantly different (p<0.001 for all items) in the test room in comparison to the standard room (Figure 107). Specifically, ratings of the items frightening, threatening, oppressive, depressed, hostile, lethargic, chilly, cool, boring, exciting, restless, business-like, formal, musty, tense and uncomfortable were lower in the test room.

Additionally, room atmosphere was perceived as less cosy, tranquil, active, relaxed, uninhibited, cheerful, hospitable, safe, mysterious, pleasant, spatial, social, inspiring, intimate, lively, luxurious, personal, romantic, calm, stimulating, warm and accessible in the standard room.

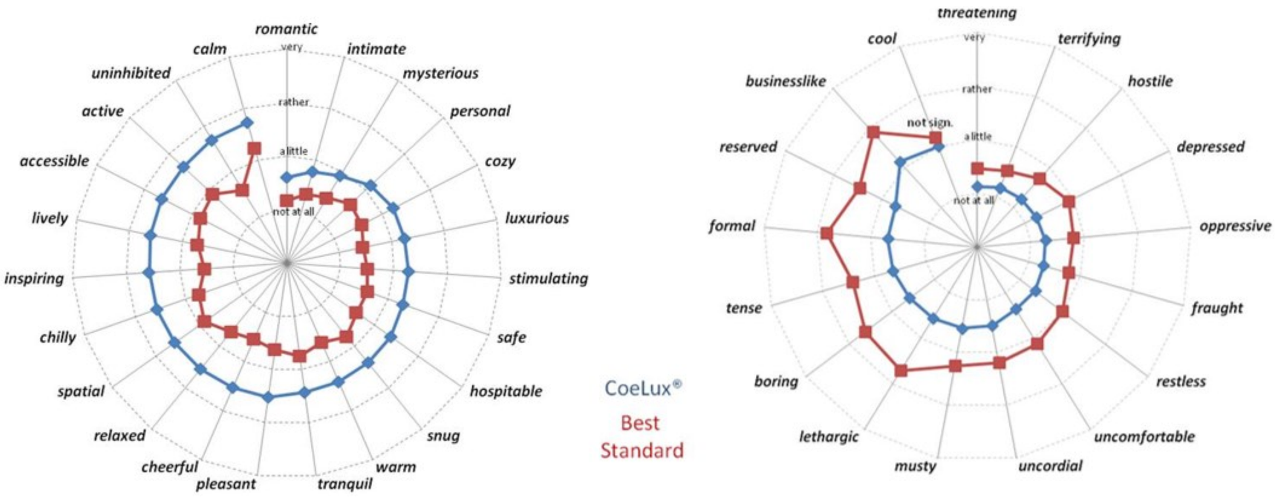


Figure 107 - Synthetic view of the perception of the two room: positive items (left) and negative items (right)

In particular the four items “oppressive”, “spatial”, “accessible” and “uninhibited” can be assigned to the category spaciousness of the test room. Noteworthy, the feeling of spaciousness as well as the naturalness of the room atmosphere, clearly support the hypothesis that CoeLux® generates a natural room impression.

It should be noted that the perceived room ambience was rated equivalently positive even after one hour exposure. This result indicates that the room impression is not subject to short-term habituation and thus emotional room atmosphere effects may cause positive long-term psycho-physiological effects.

According to the literature, especially cognitive performance parameters of people working under sunlight for several hours are higher than exclusively working under artificial lighting. Perhaps this positive day- and sunlight effect on cognitive performance parameters (such as concentration or selective attentional parameters) may also be detected under CoeLux®. It should be mentioned that recorded positive effects of CoeLux® on the subjective experience of the room atmosphere allow hoping that positive effects on work performance should be measureable after a stay in a room with the CoeLux® system of several hours.

Person-related effects

In this study, some person-related effects were studied. For example, the mood state was investigated under the two different lighting conditions, as well as claustrophobia symptoms and the State-Trait Anxiety Inventory. STAI (Julian, 2011) measures the presence and severity of perceived symptoms of anxiety. It consists of 40 items that are rated on a 4-point Likert scale. In the present study, the state anxiety subscale (20 items) was used. The total state anxiety score ranged from 20 to 80, with higher scores indicating greater levels of anxiety.

The results indicated that study participants felt more connected to the nature and perceived the windowless test room as more “lively,” and less “tense” and “detached” under artificial skylight as compared to that under fluorescent illumination. Furthermore, under artificial skylight, subjects reported lower feelings of tension, anxiety, and claustrophobic symptoms, and a higher positive mood state. Finally, subjects made riskier as well as more selfish decisions under artificial skylight (Canazei, Pohl, Bliem, et al., 2017).

In Figure 108 the result of STAI test is shown, and it is apparent the significant difference between the result obtained under CoeLux with respect to the Standard lighting (p=0.032).

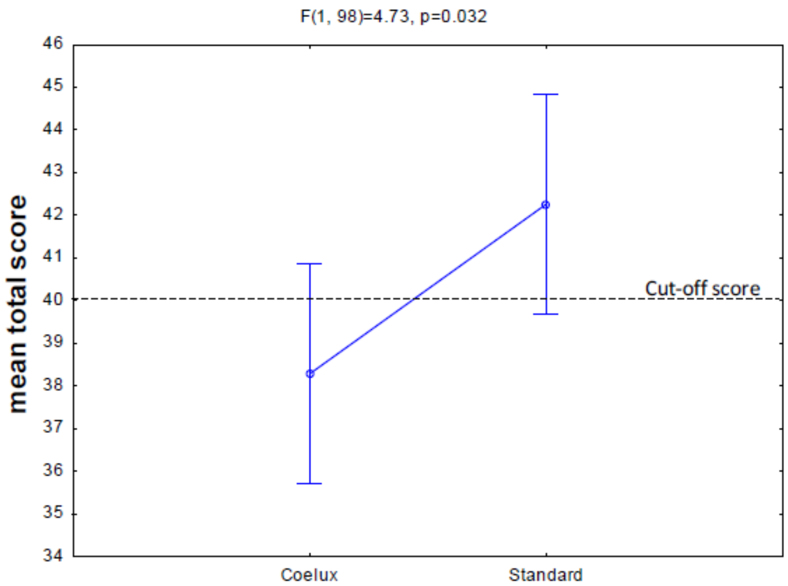


Figure 108 - STAI total scores. Cut-off score specify the clinically relevance of heightened anxiety scores.

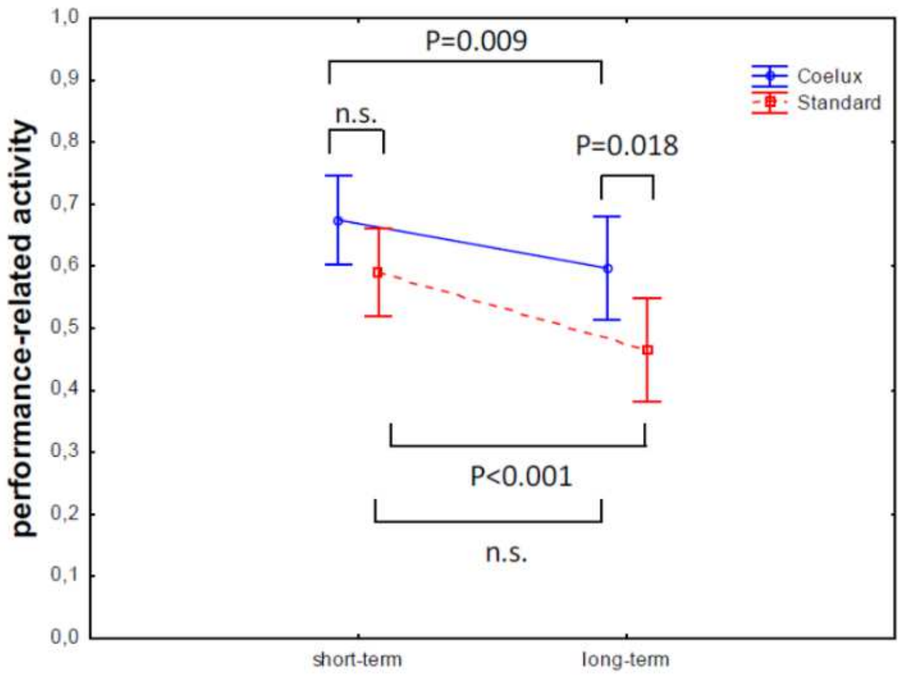


Figure 109 - Performance-related activity ratings: interaction effects between lighting condition and time

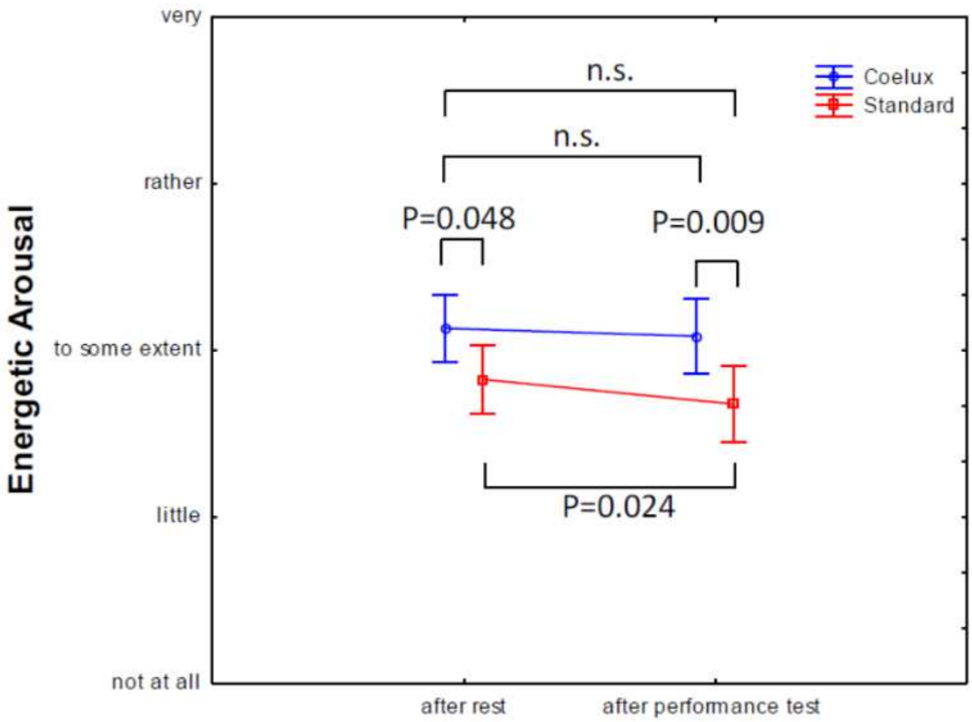


Figure 110 - Perceived Energetic Arousal

The last example reported is the "perceived energetic arousal". Scores after rest and after the performance test could reveal that these scores did not change under CoeLux. On the other hand, under standard lighting over time there was a significant decrease ($p = 0.024$, Figure 110).

It is worth mentioning that perceived energetic arousal scores under CoeLux after finishing the sustained attention test were not significantly different from scores under standard lighting after having a 3 minutes rest.

b) Calming effect

While it is true that still too little is known about non-visual lighting effects on patients in hospitals, some research exists indicating possible mood improvements and regulation of sleep-wake rhytms (Figueiro, Bierman, Bullough, & Rea, 2009; Wulff, Gatti, Wettstein, & Foster, 2010). Considering this, in the context of the EU-funded project "Deeplite", a CoeLux system has been installed in a geriatric-psychiatric ward in a regional hospital in Austria. The study performed, however, did not succeed in demonstrating mood effects, but simply registered positive feedbacks.

Later, a new study has been performed, interesting results obtained and a paper published in 2017 January, what follow is a short summary about the aforementioned results, as reported in (Canazei, Pohl, Bauernhofer, et al., 2017).

A brief description of the background should comprise the fact that only two previous works studied the mood-related effects of room lighting with high illuminance values on patients with depression and both of these showed a repeated light treatment.

On the other hand, only two studies (different from before) explored the effects of light treatments (bright in one case and colored in the other) on depressed inpatients by means of electrocardiogram (ECG). As described by Canazei et al., such results are not sufficient for wrapping up a description of bright light source effects on depressed individuals.

Following these considerations, the described study obtained innovative results under a CoeLux system.

In fact, in 2016, 21 mildly depressed geriatric inpatients were enrolled in the cited hospital and involved in the new study. In two different days the subjects were invited to follow a 30-min protocol while a multitude of parameters were measured, by means of ECG, questionnaires and a wrist-fixed accelerometer. While the activity-rest pattern and contents remain equal in both exposure, the lighting was changed, allowing for a revelation of light effects on all parameters of this balanced cross-over test. The protocol comprised both cognitive tests and resting periods, mood questionnaires as well as behavior observation.

Figure 111 - False colors image (Luminance) of the sceneview from the patient seat in Hall in Tirol clinic

Large and statistically significant effects were recorded between the two different lighting conditions: a subjective calming effect as well as a physiological effect on the heart in terms of decreased heart rate and increased vagal tone in depressed geriatric inpatients. A concise depiction of the effects is presented in the sequent Figure 112.

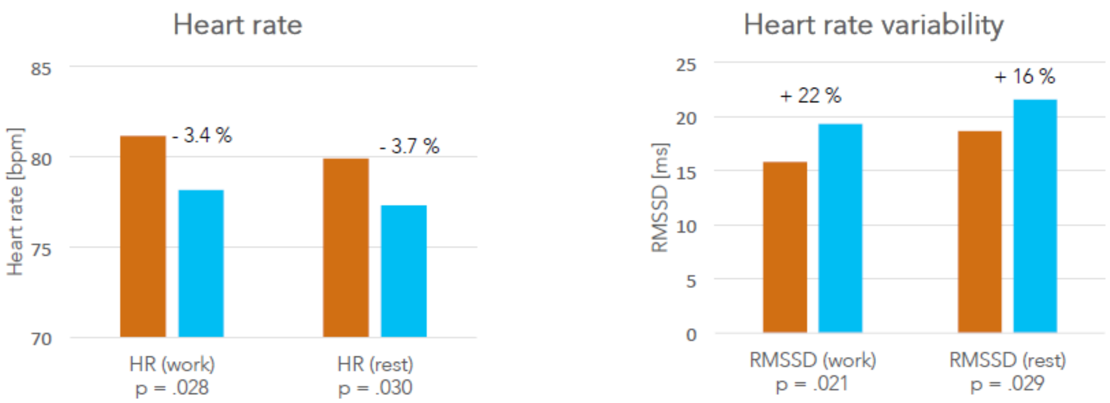


Figure 112 - Physiological results showing calming effects of CoeLux lighting (blue) with respect to Standard lighting (red).

Thereby, the present study increases the body of evidence that daylight exposure is beneficial to light-deprived hospitalized older adults and that artificial sunlight may complement prevailing or insufficient daylight levels due to seasonal or weather-related factors or due to the building environment.

3 - Whats going on

It is not easy to imagine the disruptive impact CoeLux may have in future. The elements reported in this chapter clearly advance persuasive arguments, but very different factors will condition the final result. The CoeLux technology just started to show its potentialities on the market and on influencing humans' behavior; new products are expected and a second generation has been already developed. Moreover, beyond the Sun, the Moon development allow for even different researches.

It is also true that, proceeding in the HCL, existing characteristics might be improved or new features developed according to new guidelines. Moreover, the medical perspective is already sketched with some studies ongoing, for example in a psychiatric clinic in Milan.

Perspectives and world expected outcome

It is worth recalling here the fact that some decisions in the development of lighting technologies depends from external interests. During last decades, the electricity consumption growth become a matter of discussion and an increase of efficiency in lighting would help in tackling this topic; moreover, lighting technologies may improve in relatively short time scales (P. R. Boyce & Raynham, 2009).

On the other hand, CoeLux technology differs from other lighting technology and claim to have a major impact on lighting as well as on building science.

In "The SLL Lighting Handbook" P.Boyce and P.Raynham discussed about possible evolutions of lighting. The chosen framework is the one of Maslow's hierarchy, and the authors describe possible interactions between different fields of impact of light on humans. While citing the need to belong and aesthetic needs as sometimes fulfilled by lighting, they highlight the difficulties for a complete interpretation of this market. The following citation is the final part of their handbook, written in 2009; the future will unveil how much CoeLux technologies are contributing to the scenario described there.

"So, how will lighting evolve? There will always be a niche market for sophisticated lighting, but for the bulk of lighting practice, the answer is one of two directions. In one direction the prospect is of lighting as a commodity driven solely by price with a limited range of standard equipment and designs. In the other the prospect is of a more sophisticated approach in which new technology, new understanding and new objectives combine to produce lighting better suited to the needs and concerns of mankind in the 21st century. Which of these directions lighting moves in will depend on the willingness of lighting practitioners to take advantage of new knowledge and technology and to cooperate with rather than confront apparently conflicting interests" (P. R. Boyce & Raynham, 2009).

Conclusion

Daylight essentially defines what we see, its physical characteristics are so familiar to us that any different lighting condition is immediately perceived as unnatural, or at least fake.

Moreover, natural light is characterized by temporal variations, such as the succession of day and night, that give us an additional reference (independent from any human action), implying, as an example, the regulation of our circadian rhythms.

The innovative CoeLux® technology that has been developed in the last years, faithfully reproduces the natural light.

In this work, I presented the research conducted to analyze the possible ways to realize the source which imitates the Sun. Such a research involved many different aspects of physics, technology, engineering, medicine, biology, psychology and also business.

The aim was to obtain a bright light source able to produce a high luminance and directional beam, having a circular aperture but targeting a rectangular area. Moreover, additional criteria were, among others, the high Correlated Color Temperature, the efficiency and the Color Rendering Index. In fact, no adequate light source was on the market when this research work started.

Thanks to the collaboration of external companies, my work could cover a wide range of areas of competence from optical components and light source engineering to the study of perception.

In the first part of this thesis, I briefly described natural light and CoeLux in their fundamental characteristics and effects on humans, finding the connections between the interesting sections of the research and sketching the outline of the work.

Then, in the opening section of the second part, I reported the relevant knowledge, organized as a basis to support the following steps. The described characteristics of lighting, of non-visual effects of light and of CoeLux technology served as a technical introduction to the specific research conducted.

Afterward, a significant part of my work is shown, that describes the complex and interesting collection of the analyzed aspects that have been matched: the choice of the emitter, a survey on possible optics, a brief study on LEDs, technological aspects of production, the photobiological risk...

All the above mentioned factors have been evaluated and a compromise was found to ease the manufacturing.

Then follows a description of all the actions needed to realize the prototypes, including mistakes and the corrections that needed to be made.

The conclusion of the second part shows the results of the source validation process, which took into account the functionality of the light source, as well as its certification.

The third part proves the benefits that the effectiveness of the bright light source (used in combination with the CoeLux technology) actually has on humans.

In conclusion, the research presented is thus a comprehensive work on a bright light source that has been concretely realized: starting from the definition of critical requirements, to the tests in laboratories and the final evaluation of the effects.

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