Design and development of optical, optoelectronic and sensing systems for a luminous electronic tile

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Alla mia famiglia

Table of contents

List of Figures

List of Acronyms

LUMENTILE	-	Luminous electronic tile
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
OLED	-	Organic Light Emitting Diode
PCB	-	Printed Circuit Board
PD	-	Photodiode
PMMA	-	Poly(methyl methacrylate)
PWM	-	Pulse Width Modulation
RGB	-	Red Green Blue
TIR	-	Total Internal Reflection
TRL	-	Technology Readiness Level
V2I	-	Voltage to current

Introduction

The research and development work presented in this dissertation is strictly related to LUMENTILE™ [1], a project funded by the European commission in the framework of the Horizon 2020 research and innovation programme [2]. Horizon 2020 is the biggest European research and innovation programme up to date, seven years long (2014 - 2020) and with 80 billion € funding. The scope of the programme is to enforce Europe's competitiveness by bringing technologies from the research centres to the market.

The LUMENTILE™ Project was funded in the research call having as topic "Advanced Thin, Organic and Large Area Electronics (TOLAE) technologies" (call ICT-03-2014).

The consortium of LUMENTILE received a total funding of 2.47M € from the European commission and 500'000 € from Switzerland for a duration of three years (March 2015 – February 2018).

The goal of the project was the development of a luminous electronic tile (hence the name) at a prototype level (TRL 7) for demonstration with a very small scale production. This result could enable the introduction in the market of the final product, or some of the know-how developed within. Some examples of the core technologies exploited in the project are: flexible and organic materials, large area electronics, integration of electronics and optoelectronics components with a non-standard material like ceramic as a constructive element.

The main idea and the guiding principle of the project was to create an inconspicuous device. The user should not be aware at the first glance to operate an electronic device. On the contrary, LUMENTILE™ should be perceived as a usual decorative element, turned on only after a soft interaction.

To achieve this, LUMENTILE™ was thought to resemble a standard tile in shape and materials, embedding and hiding all the electronics required for its functioning. An interdisciplinary study across electronics, software, mechanical science and building engineering was required to achieve the best possible level of integration.

Among all the technical aspects and processes involved in the design and production of the full product, the work presented in this dissertation has the focus on the electronic, optoelectronic and photonics solutions needed for LUMENTILE™.

The use of light is playing a primary role in LUMENTILE™: light is the only vehicle for the tile to communicate with the user, and is some cases presented later, it is also a vehicle for the user to interact with the tile.

The main use of light and optoelectronics is the light emission of LUMENTILE™. An efficient lighting system, and suitable light sources were to be integrated in the product, which has to offer a wide range of colours and brightness, flexible for multiple applications and use cases.

The light sources are to be hidden from the sight of the user, LUMENTILE™ should be seen as a tile having its own colour and emitting a soft light of that same colour. To do this, an optical solution managing the illumination over the surface is needed, and integration of a large area optical component inside the tile will be presented. The last application of optoelectronics in LUMENTILE™ is completely invisible and its function is to offer the user the possibility to control the tile without touching it, giving to a particular application of the tile a really fascinating interaction.

This dissertation is describing the work done by the candidate during the PhD program. The main topic of the work was solid state lighting and optoelectronic systems. Within LUMENTILE™, photonics and optoelectronics are playing a core role, being present both as light emitters, generating the actual illumination of the tile, both as the basis for sensing systems. The following work is then reporting the challenges and solutions proposed, and successfully adopted, to integrate light emitters, light guiding structure and a sensing system in the final product.

The dissertation is divided in four chapters.

The first chapter is presenting LUMENTILE™ project, giving an overview and a high level description on the system. Introducing the specifications and the requirements for lower level sub-systems.

The second chapter is addressing the light emission. The light sources considered within the project are presented, together with the results obtained in their characterisation. The architecture designed for the driving system is described, presenting the conceived method to address the single emitters in LUMENTILE™, optimising occupied area and costs of the electronics.

In the third chapter is presented the problem of obtaining a uniformly illuminated surface for LUMENTILE™. The problem arises when conjugating point light sources as

LED with a thin and frameless structure as the one foreseen by the project. A novel approach in the design of a backlighting structure is presented.

The final chapter is presenting the concept and the architecture of a gesture sensing system. This novel approach is based on optical triangulation using an infrared emitter, hidden inside the tile. The system is offering a light based proximity and gesture sensing system working through an optically opaque surface.

1 Chapter 1: The LUMENTILE™ Project

The landscape in which LUMENTILE™ was conceived is the one of the smart buildings. The initial idea was to create a tile made by ceramic, but transparent enough to let the light of some LEDs pass through the tile and give it a colourful aspect. With this idea as starting point, a more advanced goal was set, targeting the development of a product able to offer the mechanical functions of a constructive element, while being a smart device, able then to conceal construction elements robustness with the fragility of optical and electronic components.

From this basic concept, the product was envisaged as an element resembling a standard ceramic tile, incorporating electronic components inside. These components were inclusive of light sources and sensors, so that the device could be interactive with the user. The last step was adding a network feature. LUMENTILE™ is thus a decorative and building element, a light source and an interactive device; characterised by the capability of creating a network of different elements when more are connected together, able to be used as a single stand-alone device or as a group of elements acting together.

A market analysis was pursued at the early stages of the project in order to identify the scenarios into which LUMENTILE™ could be suited the most and thus specify the technical requirements for the designing phase. The outcome of this analysis was the identification of three main areas of interest: cover of walls and facades, cover of floors and large videos. From this market needs, the consortium defined three different products:

- LUMENTILE™ Wall
- LUMENTILE™ Floor
- LUMENTILE™ Video.

LUMENTILE™ Wall is dedicated, as the name suggests, for vertical installations. For this type of installation, it is important for the element to have a light weight and a fairly easy installation procedure. For its functioning, the interaction tile-user can be mainly with the hands and the action can be a gesture or a touch. This model is then requiring sensors able to detect those inputs. The finish of the surface needs to have a high quality in aesthetical terms because of the close interaction.

LUMENTILE™ Floor is designed to be deployed on the floor. The interaction in this case will be with the user walking on it. For this reason, this tile will integrate pressure sensors to detect people stepping or standing on the floor. Since the interaction with the floor tile and its use will be much harsher compared to the wall one, this model needs to be thicker and overall more resistant mechanically to be able to bare its working conditions.

LUMENTILE™ Video is supposed to be installed on internal or external building façades and used as a large video screen. The market is already offering numerous option of video LED walls of different dimensions [3] but the majority of them is meant for temporary installations and the mounting and dismounting of the structure usually involves multiple work days. The core idea of LUMENTILE™ is what makes it different from the commercial products: the Video tile is designed to be installed as a rainscreen cover on building facades; the light sources embedded in it, with the capability of creating a network will give the building a permanent wall able to display multimedia content: from advertisement, to events streaming, to a changing façade wallpaper.

1.1 LUMENTILE™ System

All the different models share the general high-level structure, and for all of them, the main requirements can be summarised as follows:

- Mechanically resistant, both during transport and during the use
- Aesthetically appealing: LUMENTILE™ is firstly a decorative element
- Electronics integrated in the structure: all the electronics needs to be integrated in the tile, and the external wiring needs to be reduced at minimum
- Light emission: LUMENTILE™ is not a common lighting fixture, the light needs to be offered in a disguised but efficient way, thus the surface of the tile needs to be transparent
- Ease of installation: the tile is wanted to be handled more as a construction object, easy to install, not as a fragile electronic device to be carefully placed and configured before the use
- Interaction: for two of the models a physical interaction is foreseen to enable some interesting use-cases.

These high level requirements, and concealing all of them at once, have guided the design and the definition of the tile structure and sub-elements as they are today.

The system is built following a *'stratified'* approach: the structure is divided in layers, each of them defined with its own specifications; every layer is connected and working in tandem with another obtaining the final structure. The four layers defining the structure are:

- Bottom layer
- Light source layer
- Light guiding layer
- Top layer

illustrated in the figure below.

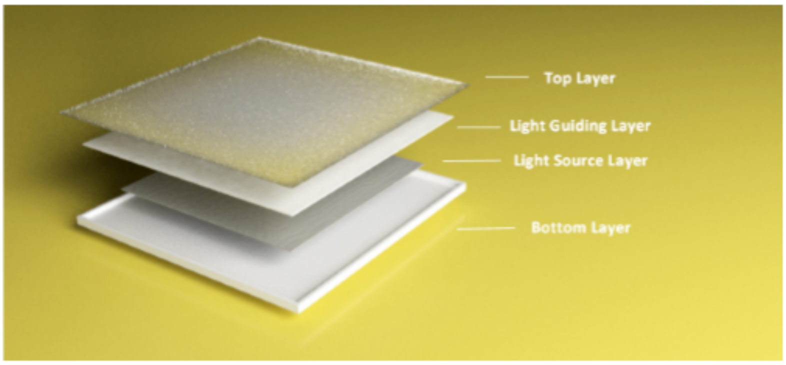


Figure 1. LUMENTILE™ 'stratified' structure, exploded view

The depicted overall structure is the same for all the model, but the materials used, the single elements and the technologies will be different, creating two different paths in the development phase: one for the low-data rate (LDR) applications; and the second for the high data rate (HDR) applications. This differentiation is linked to the refresh rates characterising the two applications. The Video tile will have a HDR oriented design, since it will need to stream multimedia content where a refresh frequency of the whole image (cover of tiles in case of LUEMTILE™) in the order of 100Hz. The Wall and Floor tiles will have instead a LDR design, because for the use cases devised for these two model a much lower refresh period is needed.

1.1.1 Bottom Layer

The bottom layer is the lowest layer and it is acting as a container for all the electronic components inside the tile. The main function of this layer is to give support to the whole device.

Although the general function is the same, the actual designs for the Video tile and the Floor or Wall one are very different.

The Wall and Floor are intended to be treated as actual tiles, adopted in installations comprising one, few or many elements. The use over the lifespan of the device is similar to the one of a standard tile; meaning it will be treated with acid, and subjected to continuous mechanical shocks.

The Video tile is designed instead to be used as a wall cover, thus not subject to shocks and treated much more rarely compared to a homeware element.

LDR Tile

The LDR tiles as written earlier will be effectively treated as a constructive element, installed on walls and floors using standard installations method. Because of this use, the bottom layer for these two models will be made by a clays dough, with characteristics similar to porcelain stoneware, a well know material in the construction environment. Porcelain stoneware is by nature a mechanically tough material, it is anti-freezing, acid and shock resistant at a sufficient level as established by standards to which all the product of this market are subjected.

The function of acting as a container, pushed the design of the bottom layer to have a peculiar tray shape, offering an empty volume inside the structure in order for the electronics to be placed, and then having the possibility to seal the electronics inside for high IP level.

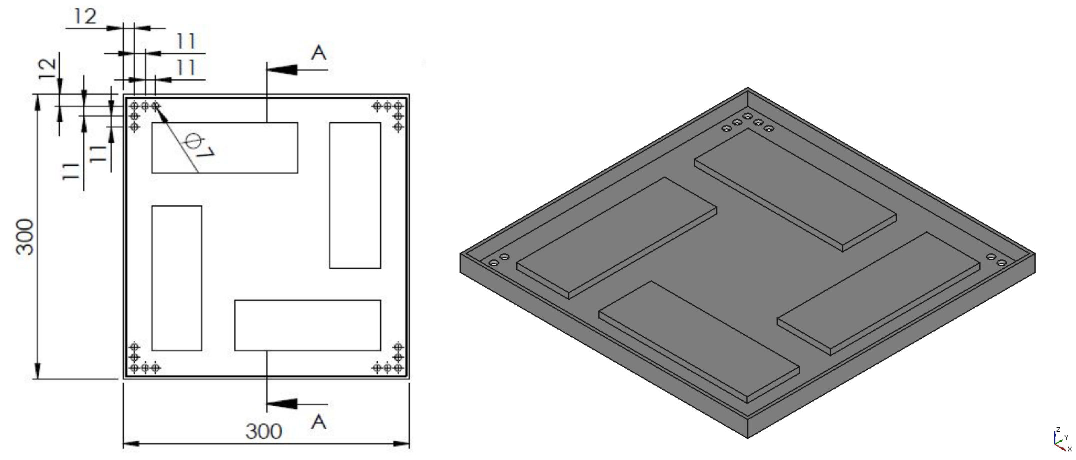


Figure 2. LUMENTILE™ LDR Bottom Layer design schematic and rendering

LUMENTILE™ though is not self-sustained under an energetic point of view, and thus needs to be supplied from an external supply. Also, the network between different tiles described before, is created through an external tile-to-tile connection which also needs to travel inside and outside the tiles [4]. For this reason, the bottom has five holes in each corner, obtaining a vertical connection from the inside to the space under the tile.

Creating holes in the corners of the tile was a very challenging step for in the development for the whole consortium.

The production process of a piece of porcelain stoneware involves in fact a lot of steps during which the clays dough is heated up and cooled down repeatedly causing the dough to continuously expand and retreat due to thermal effects. This makes really difficult the creation of the holes with a mould, but this process was the only viable one in the vision of the consortium. Other approaches were investigated, like water or laser engraving, but due to the high costs or complexity they were all discarded.

To offer the support required for the upper layer, the shape of the bottom layer is characterised by the peculiar shape shown in the previous figure.

The four rectangular pieces can be either be separate pieces to be glued on the bottom layer or being included in the mould to have a single piece. These four elements acts as columns, ensuring a wide enough surface as a support for the upper layers and the volumes between them is left to the printed circuit with the electronics, which cannot be subject to any kind of pressure from the upper layers. The PCB is thus also characterised by a unique shape and it will be described in the section dedicated to the light source layer.

In the previous figure, the holes in the corners of the tile are shown. These holes allow to provide the connection to the external environment. The physical connection to the power supply and between adjacent tiles is obtained through an additional element of the system called ConnecTile. This element is placed right in the crossing point of four tiles. The four tiles are then sharing a single ConnecTile with one of the four corners. Through this element the power supply is delivered to the tiles and the connection between different tiles is created. This component is made by several elements, illustrated in the figure below.

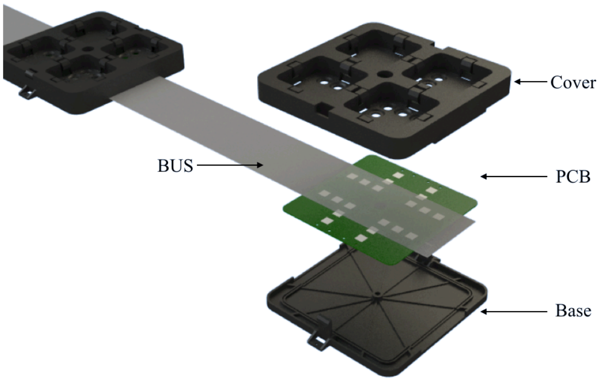


Figure 3. ConnecTile exploded view

The figure is showing four different components:

- Base: it offers a mechanical support for the structure
- PCB: a printed circuit board placed inside, it is giving all the electrical connections required, for both tile-to-tile communication signals and power supply
- BUS: this BUS, bespoke made, is made by four flat cables delivering the voltage supply to the tiles. It joins multiple ConnecTiles on a common voltage rail, supplying the power from an external ballast
- Cover: a plastic cover closing the structure. It has four trenches to host the male connectors placed on the corners of the four tiles.

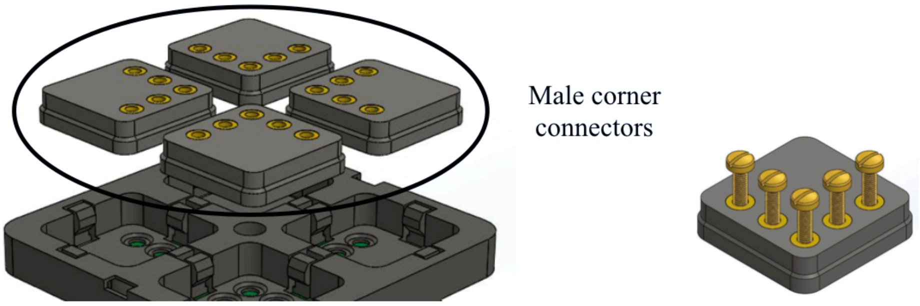


Figure 4. ConnecTile detail with corner connectors

The four corner connectors are the linking element between the tile and the ConnecTile. The corners embed a metallic cylinder with a fillet. During the assembly, the corners are put in place, the bottom layer and the PCB are placed accordingly and then five screws for each corner are fixing these three elements. In this way a tight fixing is ensured and an electrical connection from the PCB to the ConnecTile is established by the metallic screws (see figures 4 and 5).

During installation, the corners, attached to the tile, are plugged inside the ConnecTile and held in position by plastic clips inside the trenches (see figure above). The connection is strong enough to prevent the tile from falling when placed in a vertical position.

The corners are fixed on the tile with metallic screws offering a mechanical connection to the tile and an electrical connection with the electronic contacts inside the tile.

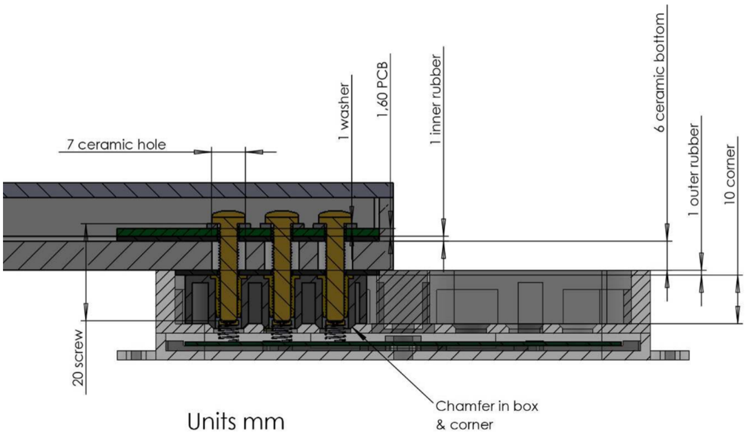


Figure 5. Tile to ConnecTile connection detail.

The tile having the corner connector fixed with the screws is put in place so that the corner is plugged into the trench in the ConnecTile. Five springs installed on the PCB in the ConnecTile are ensuring the electrical contact between the PCB inside the tile and the one in the ConnecTile.

The figure shows how the mechanical and electrical connections are provided. To ensure a consistent connection between the PCB inside the tile and the one in the ConnecTile, one spring for each contact is added in correspondence of the screw itself and soldered on the PCB of the ConnecTile. The spring is thus compressed after the installation obtaining a constant contact even in the case the tile is moving or lifting for few millimetres.

HDR Tile

For the video tile, a much lighter bottom layer was required, also, the installation of this model is thought to be made by technicians, adopting a dedicated process; on the contrary to what is foreseen for the LDR. This is due to the fact that an installation of LUMENTILE™ Video will be more expensive and fragile as it will include much more elements compared to a LDR installation, and will be made on building facades, where dedicated equipment is needed.

Because of this reason, the approach in the design of the bottom layer has been changed. A lighter structure is required, and the electronics components inside are different from the LDR ones. The cabling reduction between one tile and the other is not as restricted as in the LDR tiles, because the of the different installation approach and because the amount and frequency of the exchanged data is a lot higher than in the LDR case. This means that a more complicated connection from the inside to the outside of the tile is required. Another aspect to consider in the design was the heat dissipation. The brightness required to be emitted by a LED screen is huge, 800nits for indoor to 5000nits for outdoor screens, this means that the heat generated by the LEDs inside the tile needs to be efficiently dissipated outside the tile.

The solution to these constraints was identified in a design with a lot of structural and mechanical details, and because of this and for its heavy weight, the porcelain stoneware was abandoned in favour of a thermo-plastic compound based on polyamide, which thermal conductivity can be tuned and brought to values similar to the metal ones (1-2 W/m °K). The resulting design is shown in the figure below.

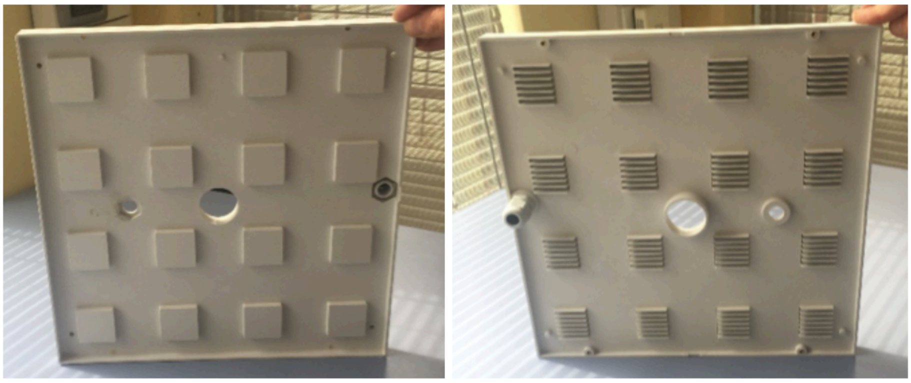


Figure 6. Bottom Layer for LUMENTILE™ Video.

Inside (left) and outside (right)

The picture above is showing a more complicated structure if compared to the LDR bottom layer. In this design there are sixteen pillars, one of them is supporting a pixel of the tile, details of this will be presented later; every pillar has on the outside bottom part some wings to improve the heatsinking; the connection to the outside environment is done through three apertures on the back. Two of them are dedicated to data transfer and one is for power supply. Referring to the right part of the picture, the first connector on the left is dedicated to the power supply cabling, the central hole is reserved for communication, from here two flat cables will be inserted to serially connect the tile to the others, the right hole is just used in the *master tile* to connect via USB the system to an external station, in charge of managing the mosaic of tile and streaming the signals to all the sub-systems of the installation.

Similarly to the LDR model, also for the HDR design, the electronic is installed in the free space left by the pillars on the bottom. In this design though, the pillars don't have a structural function, but are just supporting the LEDs. In the HDR tile in fact, the light guiding layer is substituted by a layer exclusively dedicated to the LEDs. This topic will be further discussed in the next sections.

1.1.2 Light Source Layer

Following the tile structure defined previously, the second layer of the tile is represented by the so called light source layer. This part of the tile is comprehensive not only of the light sources, as the name may suggest, but of all the electronic components in LUMENTILE™.

As explained before, the space reserved for the electronics in both LDR and HDR designs is represented by the area left free by the pillars in the bottom layer. The figure below is highlighting the available area.

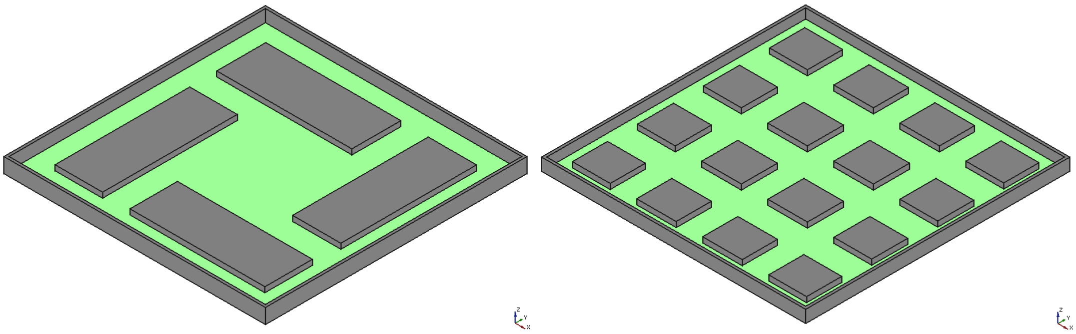


Figure 7. Area left for the electronic components

Over this area, the PCB with the components mounted onto, can extend for up to 6mm in height, giving an actual restriction in height to the components themselves of 4mm, considering the PCB thickness being almost 2mm.

Even though by a schematic point of view this layer is defined as a single layer, it is actually divided in two main parts: the PCB mounting the driving and sensing systems and a second separated one, including exclusively the LEDs. The former board (called main board from now on) is the one placed in the free space on the bottom, while the light source board is mounted in a different configuration according to the case of LDR and HDR tile.

As one can imagine from the previous figure, both the main PCB and the light source PCB are different for the two models of tile, as well as the components used because of the functionalities required.

LDR Tile

In the case of the LDR tile, the main PCB includes:

- Driving system
- Sensing system
- Voltage regulators
- CPU

Driving system

The driving system is defined as the ensemble of electronic components used to drive the current through the LED. This part will be described in detail in Chapter 2.

Sensing system

This part includes the components of the gesture and pressure sensing systems. The pressure sensing system is based on two strain gauges, acting simultaneously, which are responding to the bending of the tile when a user is walking on the floor.

The resistance of the two strain gauges is read with quarter Wheatstone bridges [5] and the analogue signal is fed to a 24 bits analog to digital converter [6]. The ADC is then coupled to the microcontroller manging the sensors which can analyse the response and identify the presence of a weight over the tile.

The gesture sensing system will be later described in Chapter 3.

Voltage regulators

LUMENTILE™ is meant to be placed in public spaces or inside private houses, where having low voltage operating devices is an important aspect. The ConnecTile bus described previously is driving the current to all the tiles installed on a floor or a wall for several square meters; and having a 220V AC supply over such a large area was not a safe option. For this reason, the choice was to proceed with an extra-low voltage supply: 24V DC. Internally to the tile, several DC-DC converters are generating from the 24V supply all the power rails for the embedded electronic components to work correctly.

CPU

Every LUMENTILE™ has two identical microcontrollers inside, working in a master-slave configuration. These two microcontroller represent the central processing unit of the device. The master microcontroller is managing the interaction with the other tiles, receiving the information regarding the condition of the tile: colour, brightness and status of the sensing system. At the same time, it transmits the same type information to the other tiles on the system. The slave microcontroller is instead in charge of operate only locally, inside the tile. It receives the information from the master microcontroller and generates the logical signals needed inside the tile. These include the brightness and colour control, the activation of a particular sensor and the reading of all the sensors inside the tile.

1.1.3 Light Guiding Layer

The most important aesthetical characteristic required to LUMENTILE™ is to have a homogeneous illumination over its top surface, so that the top finish could appear as having its own colour, without being illuminated by a light source.

To achieve this result, an additional elements managing the light was necessary, according to the type of light source used in the tile.

The final choice on the light source, as will be discussed later, was to use standard semiconductor light emitting diodes (LED).

LEDs are normally point like light sources. This means that to offer a uniform illumination, either a huge number of LEDs must be used, or an additional element needs to be used to spread the light from a point to a large surface. The technology giving a solution to this problem is well known in the display field and there are many different approaches. LUMENTILE™ though, requires a new solution in order to integrate the light guiding layer inside the tile structure as a supporting element for all the structure, while adding low complexity in the assembling phase. More than one solution has been developed within the project and those will be presented in Chapter 4.

1.1.4 Top Layer

The last layer in the stack of the tile is the Top Layer. This is the only one directly visible when LUMENTILE™ is installed. For this reason, the aesthetical appearance is the first aspect to be considered in the choice/production of this element.

The most used material in the tile landscape is ceramic, and the scope of the project, as already said, is to add a smart element to a common tile, without changing its nature.

This said, LUMENTILE™ is a light emitting fixture, and ceramic is not transparent to visible light wavelengths and this is due to its composition: ceramic is created from a dough made by powders containing particles of different sizes. Most of this particles have dimensions comparable to the visible light wavelengths, resulting in scattering phenomena, which thus don't allow the material itself to be transparent.

An additional primary aspect to consider for the Top Layer stands in its own definition. Being the most external layer, a high mechanical and chemical resistance is required since it will be continuously stepped, washed and exposed to the external environment agents.

One of the member of the consortium, KERAPLAN™ [7], raised its interest in developing a transparent ceramic compound, offering a high transparency and able to bare the loads LUMENTILE™ is exposed to.

A continuous collaboration between the University of Pavia and KERAPLAN™ has been held in order to find the best dough in terms of optical properties, without sacrificing the mechanical characteristics required to the layer.

The final result has been the development of a translucent ceramic layer, where transparency is achieved through a particular mix of different powders and a cooking cycle proprietary of KERAPLAN™, where temperature and cooking times at the multiple steps of the process are applied.

The three different models of LUMENTILE™ are asking for different requirements and performances. The Wall Tile for example is the one which has the closest interaction with the user, thus a good look is a fundamental aspect. The Floor Tile on the other hand is requiring mechanical resistance in the first instance and the light emission quality and efficiency can be secondary. The Video Tile instead, is supposed to be observed from a long distance, thus the close appearance is not important at all, while the high brightness and efficiency required are fundamental characteristics to satisfy. An example of this concept is shown in the figure below.

These different requirements are translated in three different type of top layers, where the primary characteristic required for the particular application is the focus for the material identification for the top layer.

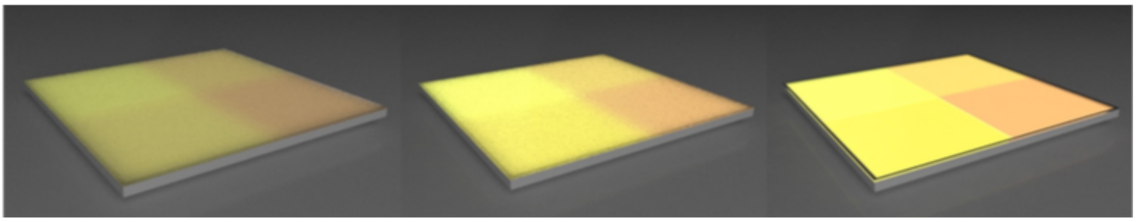


Figure 8. Different aspects of lit LUMENTILEs.

The Floor Tile, first left, can be more opaque, light quality is secondary; the Wall Tile must have a good looking surface, but efficiency needs to be as high as possible; the video tile has no *requirements on the aspect, the top layer has only the function of covering the electronics from the external environment, while transparency is the key aspect.*

LDR Tiles

The Floor tile needs to have the highest mechanical load resistance among all the models. Also, it is the most exposed to chemical agents, thus corrosion and erosion resistance needs to be high as well. Since it is installed on the ground it must be walkable, thus anti-slippery and anti-freezing are required aspects from a safety point of view.

Ceramic is satisfying all the above requirements and because of this, the ceramic top layer developed by KERAPLAN™ was selected as the top layer for the Floor tile. The picture below is showing the resulting ceramic created with their process.

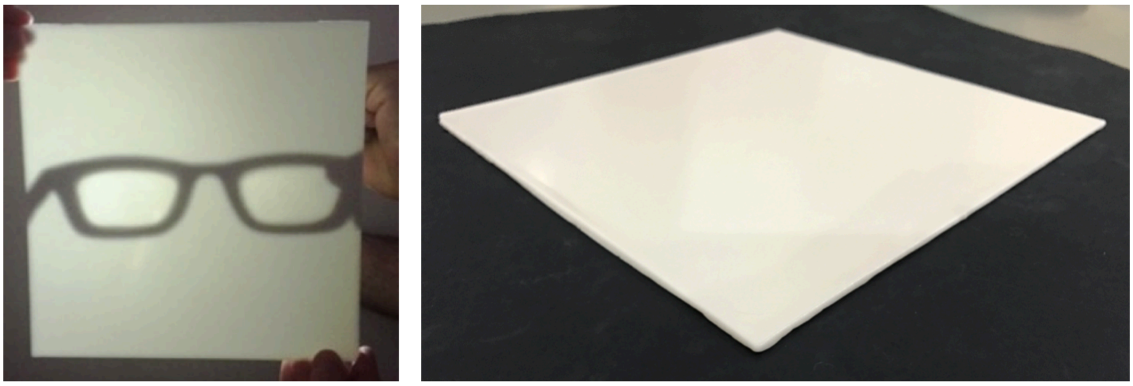


Figure 9. Ceramic top layer developed by KERAPLAN.

The left picture gives an idea of the transparency achieved by this material.

The interactions foreseen for the Wall Tile do not require any mechanical resistance, and no safety feature is required to the surface like in the case of floor application. Thus the top layer is chosen by looking at power efficiency and aesthetical appearance.

The compromise was found in a product developed by OmniDecor [8], a particular tempered glass which is covered by a very thin (<1mm) layer of ceramic based enamel. The advantage of using this glass is that the top surface is actually ceramic, but the thickness of it is so reduced that the impact on the light transmission is low. The final visual effect is exactly the one envisioned by the project. This glass though, does not have the necessary safety requirements to be installed on a walkable floor, thus its use must be limited to the Wall Tile.

Figure 10. Top layer in glass with white ceramic enamel

HDR Tile

The HDR tile isn’t requiring any type of mechanical resistance, it will be installed as a cover of facades or in interior spaces. The interaction with the user will be at a distance of several meters, meaning that aesthetic and safety requirements don’t play any role for the top layer selection in the Video Tile. The only parameter to be optimised is optical efficiency, thus, the option is a completely transparent Top Layer. In order to keep the cost as low as possible, the choice was using a 2mm thick acrylic (PMMA) sheet, fully transparent. Other options were considered like glass and polycarbonate. Glass is too heavy compared to plastics thus not desired for the type of installation of the Video Tile. Polycarbonate offers an even lower cost compared to PMMA but it is more sensible to the UV radiation, causing it turning to a yellowish if exposed at sunlight and this could alter the image quality over time.

2 Chapter 2: Light Sources and LED Driving System

This chapter will focus uniquely on the Light Source Layer. The challenges and the adopted solutions to solve these challenges will be presented.

2.1 Light Sources

In LUMENTILE™, the vehicle to convey information in response to an action, is light.

During the course of the project two different light sources has been considered for the adoption in the final product. Semiconductor based light emitting diode (LED) and organic light emitting diode (OLED) were the options as light source for the tile.

RGB LED

In 2014, I. Akasaki, H. Amano and S. Nakamura were awarded the Nobel Price "for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources" [9]. Since then the LEDs have seen the adoption as light source more and more, and the demand for blue LEDs for white light has caused also technology improvements common to all the other wavelengths of emission.

Light emitting diodes are devices which emit light due to electroluminescence. They are constituted by a p-n junction trough which an electrical current is flowing. After the creation of electrons and holes pairs due to the current flow, their successive recombination creates photons which are emitted out of the device. The frequency of the photon is determined by the bandgap value of the semiconductor material used and many alloys are offering bandgap values to generate photons at visible frequencies.

LUMENTILE™ in its current models is adopting RGB LEDs.

Historically, the first semiconductor based LEDs being developed have been in the infrared range, based on Gallium Arsenide alloys (GaAs) [9]. The first visible range wavelength was in the red part of the spectrum and developed by General Electric [10].

Today, visible light emitters are available in different emission wavelengths and different power levels.

In order to cover most of the visible spectrum, three different LEDs, green blue and red emitting are used together and the emission is tuned to obtain the desired hue.

To create the single colour emitters, some of the most commonly used compounds are: Aluminium Gallium Indium Phosphide (AlGaInP) for green; Aluminium Gallium Arsenide (AlGaAs) for red; and Indium Gallium Nitride (InGaN) for blue.

OLED

A different technology is offered by Organic LEDs. One of the member of the consortium, VTT [11], has an important background in designing and manufacturing OLEDs, in particular flexible ones, using a very cost efficient process: printing.

An OLED is usually made by a thin layer of organic compounds, closed in between an anode and a cathode; the stack is then deposited on a substrate which can be rigid or flexible [12]. The OLED developed by VTT have a structure based on the thin film polymeric layers and are typically printed on transparent, flexible plastic films. An advantage offer by this technology is the possibility to print OLED structures over large areas. However, these structures often generate low efficiency devices compared to vacuum evaporated devices. The organic materials used for the OLED are in fact very sensible to oxidation; and the exposure to air must be reduced at minimum during the fabrication process. Moreover, the flexible enclosure, necessary for the roll-to-roll manufacturing, offers a sealing capability much weaker compared to rigid substrates. For this reasons the short lifetime due to exposure to air, both during the fabrication and during the use of the OLED is the main issue in the adoption of this technology in large area lighting systems.

Figure 11. OLEDs printed by VTT. (Credits to IN-LIGHT Project [13])

This said, the OLED is well accepted and spread in smaller areas application, where efficiency and colour quality are key aspects and manufacturing cost is not an issue (mobile and TV display applications).

The OLED produced by VTT have been tested in order to assess their usability in LUMENTILE™. The light uniformity of the devices was perfect: the light is created over all the surface evenly. After few months though, the samples showed massive degradation in light emission and many black spots appeared in the device. In the figure below the dark areas can be observed, in these zones the organic material is not able to create light anymore. To be noted that this degradation was only due to use in the laboratory, where simply the air exposure generated an accelerated ageing process to the samples.

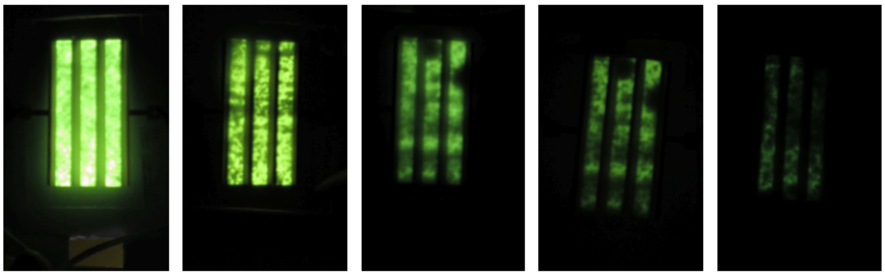


Figure 12. OLED tested samples

The evaluation on the OLED is suggesting that the technology is promising but not mature enough, and yield and lifetime of the finished OLED sheets are still an issue, meaning that today they cannot be considered as a light source for LUMENTILE™.

RGB LED Experimental Characterization

After this analysis, standard LEDs have been selected to be the light source of LUMENTILE™.

LUMENTILE™ is a colour changing light fixture, supposed to change colour according to the desired use. This of course means that the LEDs need to offer red green and blue components of the spectrum (RGB) so that every colour between the red and blue wavelengths can be covered.

The LED chosen for LUMENTILE™ are from the Luxeon Z Color series by Philips - Lumileds [14]. The main features of these LEDs are:

- High DC forward current limit (up to 700-1000mA). It is important to reduce the number of devices used.
- Good efficiency: 30lm/W for blue; 54lm/W for red; 71lm/W for green
- Small form factor: $1.3x1.7x0.7mm^3$. The package with no additional optics allows small device dimensions.

The reduced size and the high brightness offered by these devices make them one of the most suitable LEDs for our application.

LEDs always show a higher efficacy when they are supplied with alternated current. This behaviour is related to two main reasons: the reduced efficacy when the temperature of the junction is increased and quantum effects.

The temperature of the device, and thus in the junction, increases when a continuous current is flowing through the LED: this reduces the electrical to optical conversion efficacy of the LED and gives rise to other undesired effects [15].

The second effect is linked to Auger recombination [16] [17]: the Auger recombination is shown by LEDs when the carrier density in the junction reaches a high value and the percentage of the radiative of recombination decreases, decreasing the efficacy of the device. The figure below is comparing the light emission of the three selected LEDs when driven with DC or AC current at 33.3% duty cycle.

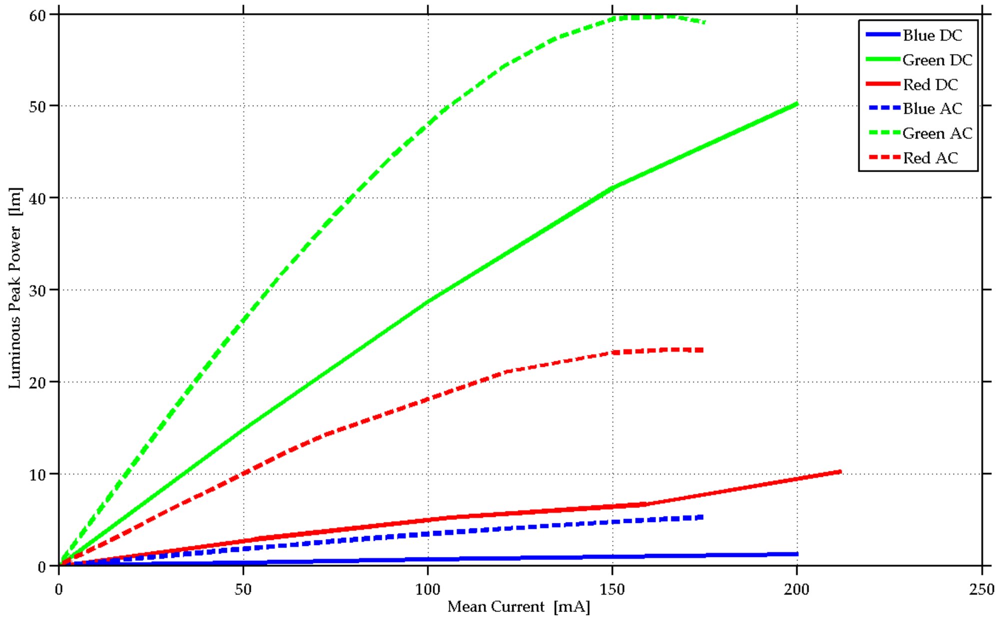


Figure 13. DC and AC driving for the selected LEDs

For these reason, an alternate current driving has been implemented in LUMENTILE™ to optimise the plug efficiency of the device. Its architecture will be described later in this chapter.

2.2 Light source integration

The process of embedding light sources in a large area device is not a new challenge in the optical field. If one thinks at any sort of display, these are basically large area surfaces with a backlighting system giving the white light background. In displays, this light is used as a base for a RGB pixels matrix based on liquid crystals, which are individually controlled to obtain the coloured image.

There are two standard approaches in designing a backlight structure for displays: side configuration and direct configuration. The two differ in the placement of the backlight sources inside the structure.

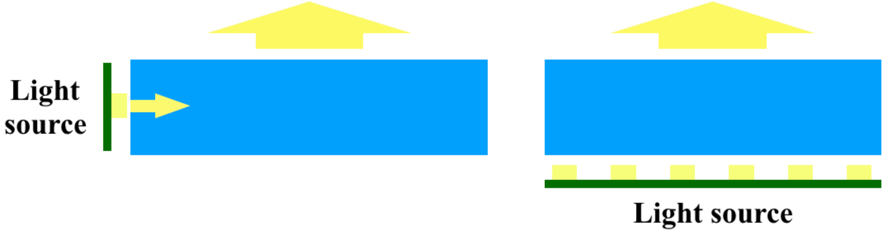


Figure 14. Side configuration backlight structure (left) and direct (or planar) configuration backlight structure (right)

With “light source” from now on we will mean LEDs but the basic structure for backlighting in displays are much older than the LED technology, and the basic approach remains the same even if the light sources have evolved. Before the advent of LEDs, the light source for backlight were mostly cold cathode fluorescent tubes (CCFT). CCFTs were more advantageous in terms of designing the backlighting system in both cases of a side or direct configuration. CCFTs in fact are tubes and all the areas covered by the tube is illuminated at a uniform level. The LEDs are instead point like sources with a Lambertian emission, thus when installing many of them together, an ensemble of light spots is generated.

Also, since the LED are intrinsically ‘discrete’ light source, the number of LEDs is always increasing with the area to be illuminated, together with the cost. In case of a CCFT, the shape of the tube can be design to occupy a defined area and the cost is not linearly increasing with the illuminated area.

Given all this, LEDs are bringing many advantages compared to CCFT. The main ones are related to:

- hazard and safety: CCFT contain Hg, LEDs have no dangerous materials
- mechanical shock: CCFT are made of glass, LEDs have no breakable part
- voltage levels for operation: CCFT operate at very high voltages, >1000V [18] while a LED backlight is operated at few tens of volts, accordingly to the number of LEDs and their connection

- dimming: CCFT are difficult to dim precisely and over the whole intensity depth and the dimming operations can be damaging for the tube itself; LEDs are easily dimmable with pulsed current or controlling a continuous current level, precisely over 1 to 100% of the intensity.

Anyway, CCFT are a surpassed technology and as already said, LEDs have been the light sources selected for LUMENTILE™. Their placement inside the tile is following the approaches depicted above and used in the display technology.

The HDR and LDR tiles are using two different approaches for embedding the LEDs inside the tile, due to the different requirements and the different designs of the two models.

LDR Tiles

The LDR tile is requiring a lower brightness compared to the HDR application while it is really important for this model to be characterised by a uniform illumination of the surface. The actual solution to this challenge will be described in depth in chapter 4. The starting point for the final design is using a side configuration backlight and a light guide (constituting the light guiding layer).

The main issue in adopting a planar approach, is the higher thickness required by the light guiding layer to obtain a uniform illumination. In LASSIE [19], a FP7 European project, many solutions have been presented and developed. Using micro-structured elements, it was demonstrated that the thickness of the layer should be comparable to the pitch between the LEDs. This approach is impossible in LUMENTILE™ because the required number of LEDs would imply high cost and a more difficult and fragile assembly process.

LUMENTILE™ is offering a coloured light thus the light sources of the previous figures consist now in RGB LEDs triplets.

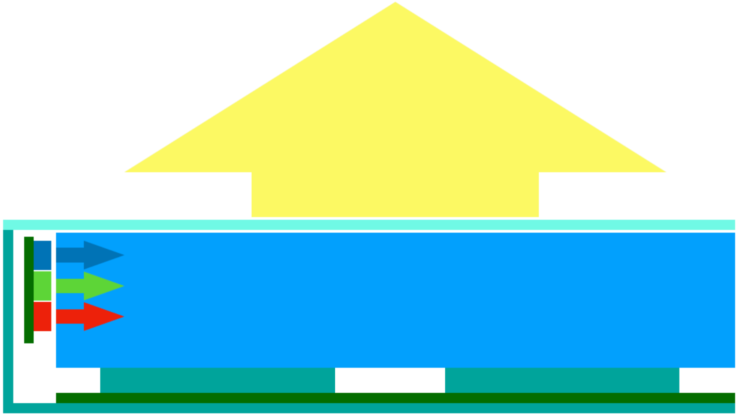
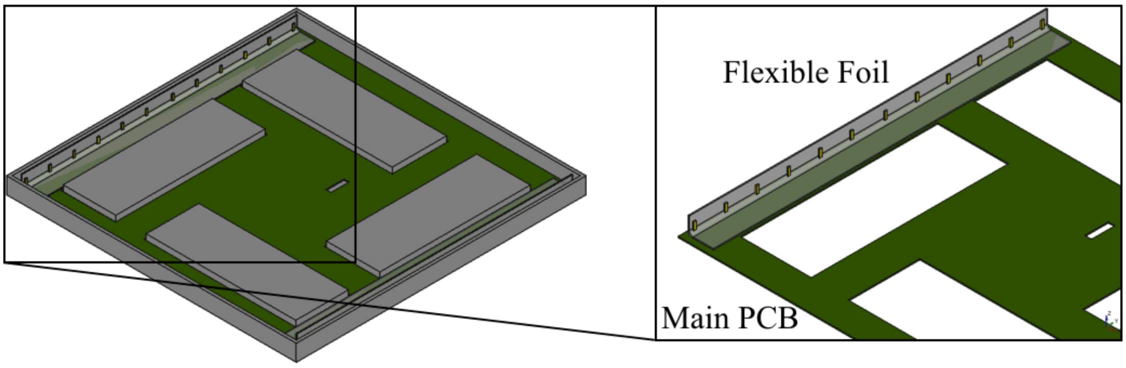


Figure 15. Edge backlight configuration in LUMENTILE™

In a standard display, the LEDs and a voltage converter are the only electronic components, thus a single PCB is placed close to the light guide and connected to the supply, or in some other cases, a LED strip is connected through cables to a voltage converted placed somewhere behind the screen. In LUMENTILE™ this structure is more complicated. The Main PCB is hosting all the electronics and it is placed lying on the bottom layer as described previously, then the pillars are sustaining the light guide, to which the LEDs need to be coupled. A solution was needed to connect the LEDs to the main board.

The technology owned by VTT of printing flexible substrate with conductive tracks pave the way to an idea of producing a flexible LED strip with the LED mounted onto and the tracks connecting the LED to the main PCB. This solution is illustrated in the figure below, with one of the strips printed by VTT and used in a prototype of LUMENTILE™.



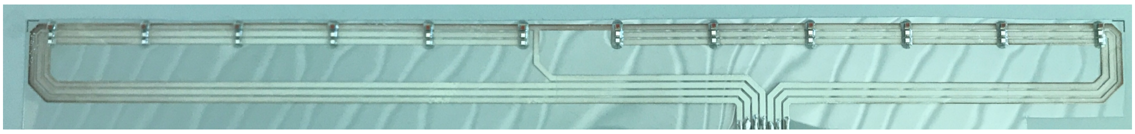


Figure 16. Flexible foil and main PCB installation within the tile (above) and flexible foil printed with the LEDs mounted (below)

This approach has the advantage to reduce the production cost of the light source PCB exploiting the processes of the printing technology. The greatest problem with this solution is though represented by the coupling to the light guide. The coupling in the backlighting systems needs to be really precise both in the distance between the LEDs and the light guide, which has to be as small as possible; and in the positioning of the LEDs in front of the light guide.

The flexible substrate though, is not, by definition, self-sustaining; this means that a support is needed. In case of LUMENTILE™, the bottom layer itself, with its tray shape, is in principle offering walls to stick the flexible foil onto, fixing them in a certain position. Nevertheless, the dimensional precision reached by the bottom layer in ceramic is ±2mm and this tolerance is too large for the precision required in the light coupling process.

For this reason, the solution was found in using a standard FR4 PCB also for the light sources, to be fixed directly onto the main PCB, making the LEDs board agnostic to the ceramic tolerances and to the bottom layer shape. This rigid connection is achieved with a couple of connectors for every light source PCB, one of them supplying the current to the LEDs, and the second being a dummy one, just to ensure the mechanical connection of the two boards together. The figure below illustrates the concept, showing four different light source PCBs, one for every quadrant of the tile; and the actual PCBs connected together in the final design.

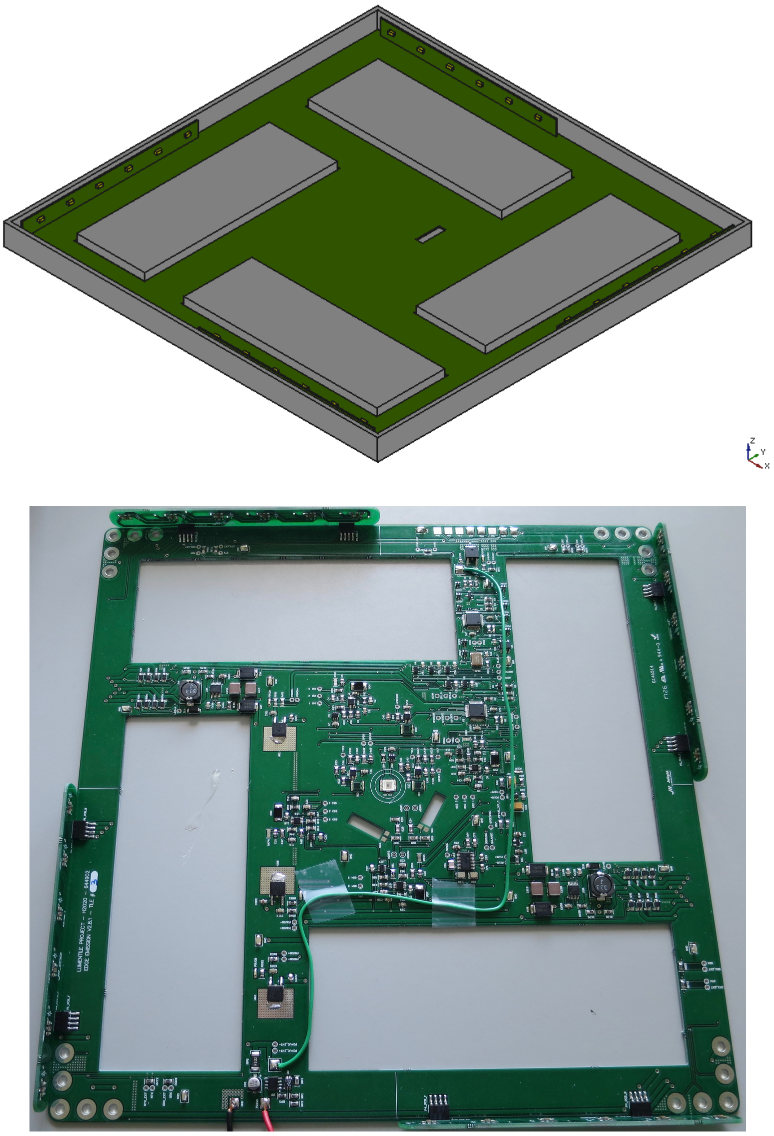


Figure 17. LDR Tile: Main PCB and Light sources PCBs connected together (below) and conceptual installation of the two in a tile (above)

This solution has a higher cost compared to the one using flexible printed foils, but the performances and the robustness are much higher, ensuring an easier assembling process and a better visual result.

HDR Tile

In the case of the HDR Tile, the desired visive effect was the one of a large video-screen where small surface light elements are associated to pixels. To do this, the brightness of each pixel has to be as high as possible, and staring directly to the LED itself is the best way to obtain this. This concept is the base of almost all the LED walls found everywhere in large screens or advertising panels [20].

According to the single project and the use case requirements, the LED can be then covered with a diffusing sheet, or left uncovered to get the maximum brightness.

The concept just described is actually the approach used in the direct backlight configuration, where the LEDs are placed on the same plane of the display surface.

In the display field, this approach offers many advantages, one being the highest degree of freedom in regulating the local intensity, and most importantly, placing the LED in a direct configuration is giving the highest brightness. Nevertheless, the cost is very high compared to the edge configuration, due to the greater number of LEDs used, scaling linearly with the area increase. A second disadvantage is that the direct configuration is requiring a thicker structure to obtain a uniform illumination, and this is not always possible or desired; like in LUMENTILE™ LDR. Although this is not true for the Video model.

For LUMENTILE™ Video, this approach is the one adopted and the only reason is the higher brightness. The work done with VTT also allowed to use the printing technology to keep the costs contained, since the area needed for the light source PCB is for the video tile almost equal to the whole area of the tile: 30cm x 30cm. This means that using FR4 with the standard chemical etching process would imply high cost and incredibly high production waste since the utilised area is a very small portion of the whole.

The number of pixel into which a single tile is divided in 16, each of them is made by 5 RGB triplets with the same LEDs used for the LDR tiles. Every Video Tile is thus integrating 240 LED chips, mounted on two different foils large 28cm x 14cm. The foils are placed onto the pillars of the bottom layer and connected to the Main PCB through a zero insertion force (ZIF) connector. The male contact is not a flexible cable but it is substituted by the foil itself, onto which the tracks are printed with the same pitch of the connector, and fixed in the female.

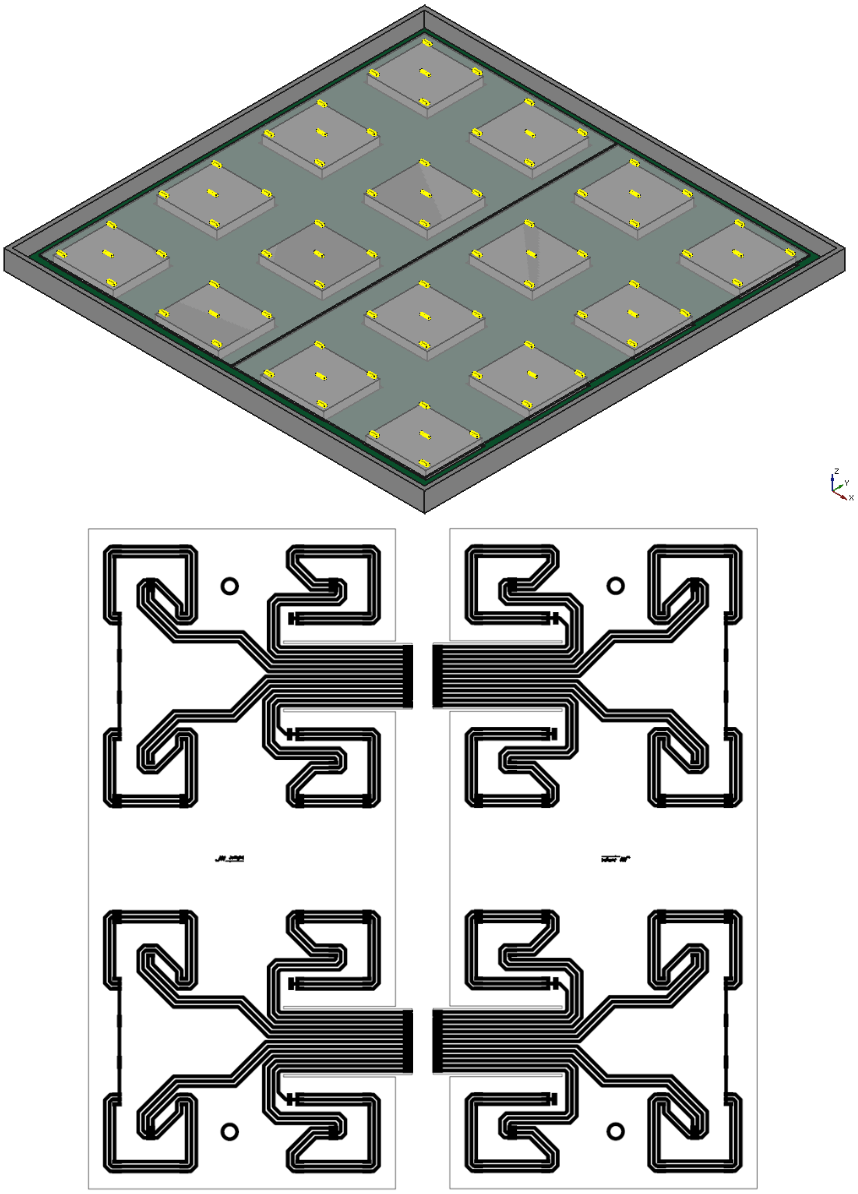


Figure 18. Video Tile: conceptual integration of the light sources foils and main PCB in a tile (above) and the layout of the foils (below).

The flexible foils are made by PET and the tracks are printed with silver based ink made by Asahi [21]. The LED are attached to the foil using a conductive glue [22] because a standard soldering process at high temperature is not viable with this technology, since it would melt the plastic substrate. The Video tile structure as depicted before, is not comprehensive of a light guide and the top layer is made by transparent PMMA, this implies that everything inside the tile is visible. Having a PET foil as substrate gives the advantage of the possibility of adding a pigment to the PET itself or easily paint it later with the desired colour hiding completely the electronics laying below the foils. For the final prototypes is LUMENTILE™, a thin black vinyl foil was glued on the PET foils, covering the electronics below.

2.3 Light sources driving stage

To obtain the highest possible plug efficiency, a dedicated design was developed for LUMENTILE™. The starting point has been presented before, and implies using an alternate current driving for the LED, improving their efficacy. Also, the adoption of an alternate driving makes most immediate the tuning of the colour components when mixing them for the resulting light colour. In fact, with an alternate supply the adoption of a pulse width modulation is immediate since it allows to precisely control the average value of current, thus, the emitted power.

The driver needs to be able to be used in a pulsed regime with a controllable frequency and a variable duration of the pulses. The most adopted commercial solution for LED driving systems is using a buck converter. A buck type converter is a switching DC-DC converter which steps down the input voltage to a lower one without sacrificing the efficiency like linear low dropout DC-DC converting (LDO) circuits. Normally they contain a diode, an energy storing component (usually an inductor) and a MOSFET controlling the current flow through the inductor. For LUMENTILE™ implementation, the selected device was a buck converter by Texas Instrument [23], able to offer an output voltage drop of up to 45V.

The choice of using a buck converter implies a maximum output voltage <24V, which is the input rail for the tile, as said before. This maximum is thus limiting the number of LEDs supplied by the driver, since the connection of the devices is made in series. Every colour can thus be composed by a maximum of 6 LEDs connected in series, through which a modulated current with a peak of 750mA is flowing.

The most immediate design is reported in figure, where every colour is driven by an independent driving stage regulating the single colours intensity.

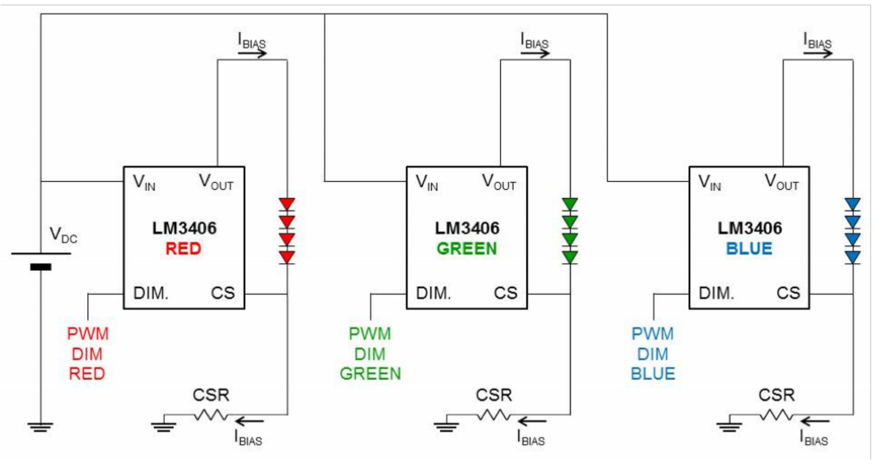


Figure 19. Driver architecture where every colour is controlled independently by a single driver

For the implementation of this architecture we need to consider that in LUMENTILE™, the desired appearance of the surface of the tile is to be divided in 4 different and independent quadrants, every quadrant able to display every possible colour, thus having red, green and blue LEDs. This decision, when adopting the architecture depicted in the previous figure, would have implied to use 12 drivers, one for each colour, and three for each quadrant, implying a cost increase for the tile both in components and assembly cost and in the design complexity.

To improve this aspects, a new design and a related driving approach were proposed. The idea is based on multiplexing in time the colours and the quadrants of the tile, allowing thus to use a single driver, feeding every LED during different time frames, across every colour time window, a PWM is then superimposed to regulate the specific weight of that colour in the quadrant hue.

The architecture to allow this operation is using transistors acting as switches and guiding the current in the dedicated colour. One of the transistor is placed below the series of LED, to control the single colours weight, while the rotation of the different quadrants is obtained with a second transistors over the series, selecting the *active* quadrant in that specific time interval. In the actual design this transistor is a n-channel MOSFET, which gate is controlled by a logic signal coming from the microcontroller already installed in the tile.

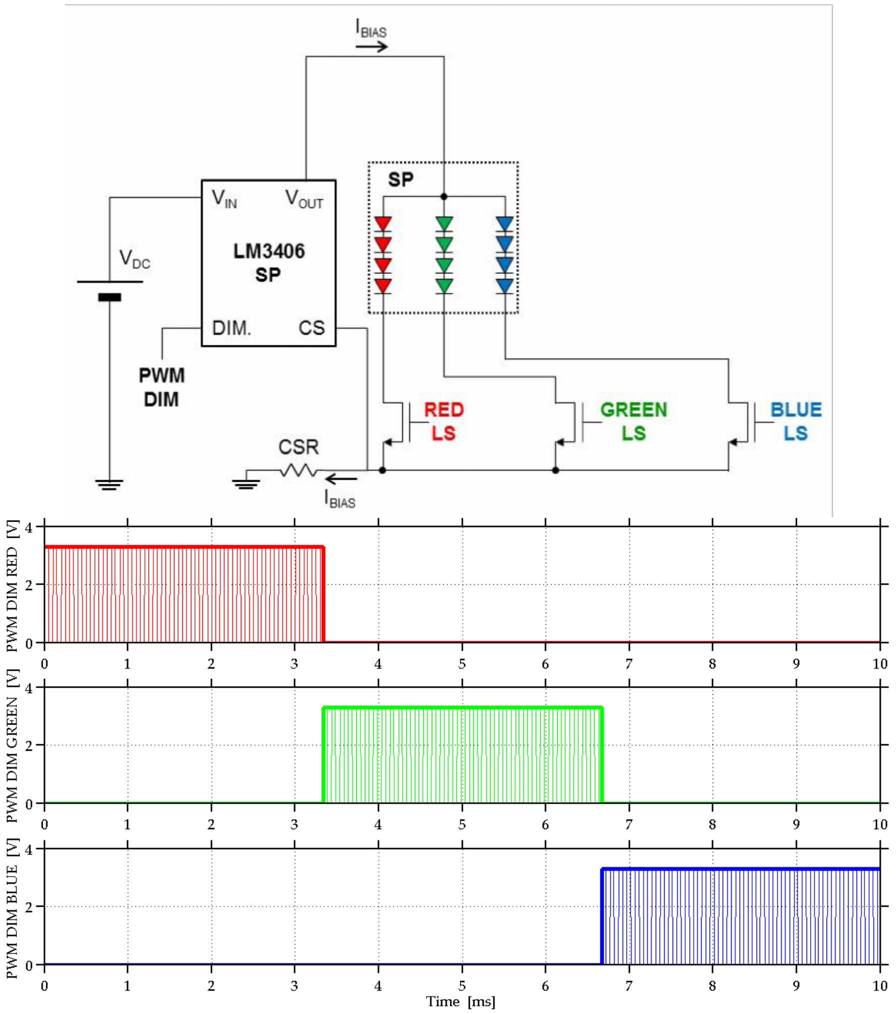


Figure 20. Block diagram and time diagrams detail.

The upper image is reporting the block diagram of the proposed driver architecture for a single quadrant. SP is indicating a single quadrant of the subpixel. I_{BIAS} *is the driving current flowing into the LEDs RED LS, GREEN LS and BLUE LS are the logical signal controlling the transistors coming from the microcontroller. PWM DIM is a PWM signal, coming again from the microcontroller, regulating the dimming of the colours. The lower image is reporting the time diagram of the logic signals over which the PWM is superimposed.*

In the earliest prototypes the proposed design, with all the quadrants and all the colours driven by a single driver was installed and used. The light intensity resulting was not high enough though, due to the low transmission efficiency of the ceramic top layer. For this reason, the same approach but using two drivers, controlling two quadrants each was adopted in order to double the average current flowing through a single colour, and consequently the emitted light power. The final schematic is reported below with its time diagram for two of the quadrants.

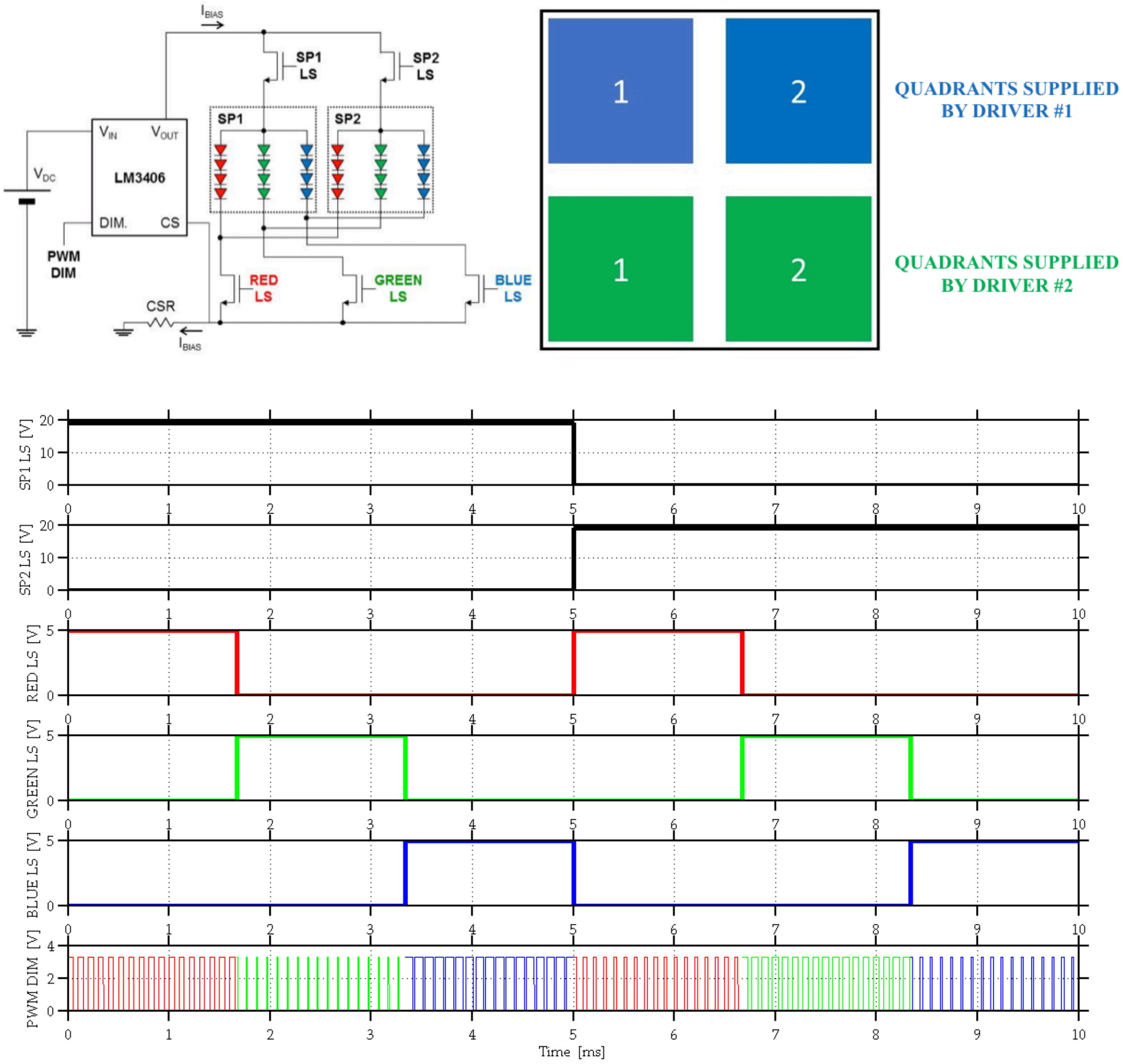


Figure 21. Block diagram and time diagrams detail.

The upper image is reporting the block diagram of the driver, SP1 LS and SP2 LS are the logical signals controlling the two transistors associated to the quadrants. RED, GREEN and BLUE LS are as before the logical signals controlling the "colour" transistors, PWM DIM is controlling the dimming and CSR is a current sense resistor which value is imposing the current I_{BIAS} driven though the LEDs. The lower image is reporting the time evolution of the signals reported on the y-axis. It is important to be noted that the signal, like the transistor controlling the colour is shared between two different quadrants, in fact the "on" state of a single colour of a certain quadrant is selected through a Boolean AND between the quadrant and the colour signals (SP#* LS and *Colour* LS) while the PWM DIM signal is in common for all the colours, it is synchronised with the logical signals to obtain the correct colour at the correct time.*

The procedures just illustrated are time dependent and the describer situation involves a sequential evolution of colour and quadrant signal, over which the non-active colours are switched off. The timescale of these operations is much lower than the one the human eye is able to perceive: the PWM DIM signal has a frequency of 10kHz the frequency of the SP*#* LS is 100Hz while the *Colour* LS is 200Hz. The highest frequency for a blinking light to be perceived by the human eye is usually around 50-60Hz.

A final assessment on the efficiency of architecture described has been done through an intensity measurement in function of the duty cycle. The curves below are reporting a lux emission using an AC without multiplexing colours and pixel (meaning each colour has a single driver) and the architecture described above, using the colour and quadrant multiplexing. The average current for every colour is kept at the same level in both cases.

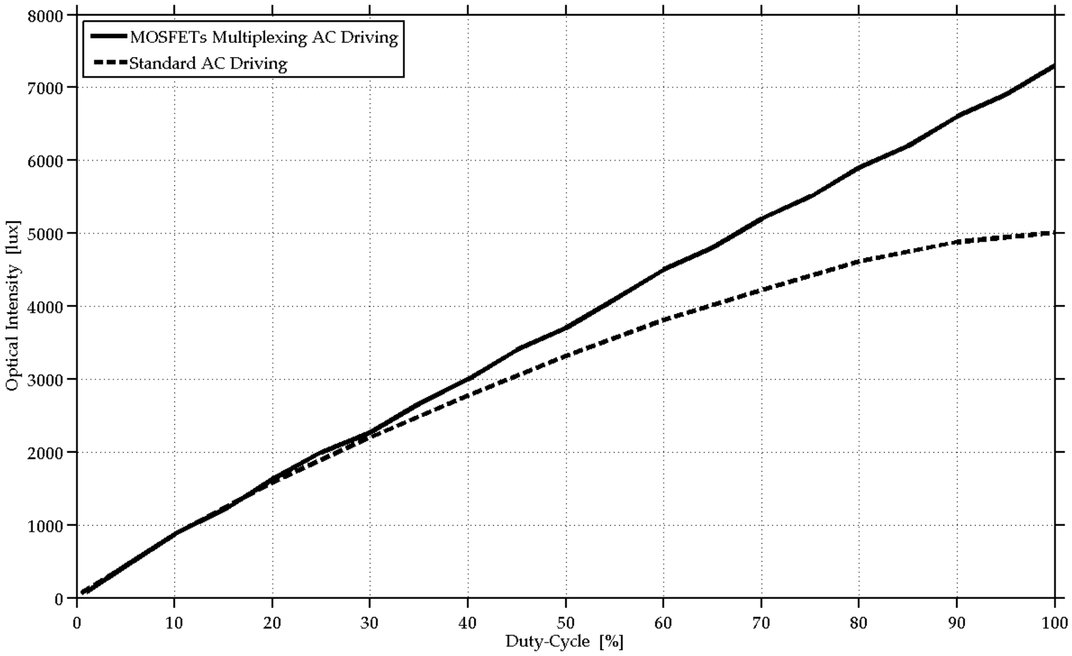


Figure 22. Optical intensity vs duty cycle

It can be seen that the efficiency droop is no longer an issue for the performances. The size and cost reduction are significant: from 7% to <1% in area occupation and the cost is reduced to 16% of the one using the initial architecture with one driver per colour.

HDR Tile

For the HDR tile, the approach is analogous, here the tile is divided into 16 sections instead of 4 and the area reserved for the electronics is smaller, thus the impact of this architecture is even more significant. The number of driving stages is 4, each of them is driving 4 different sections (sub-pixels) of the tile. The figure below is reporting a scheme for this together with the schematic of each of the four different drivers.

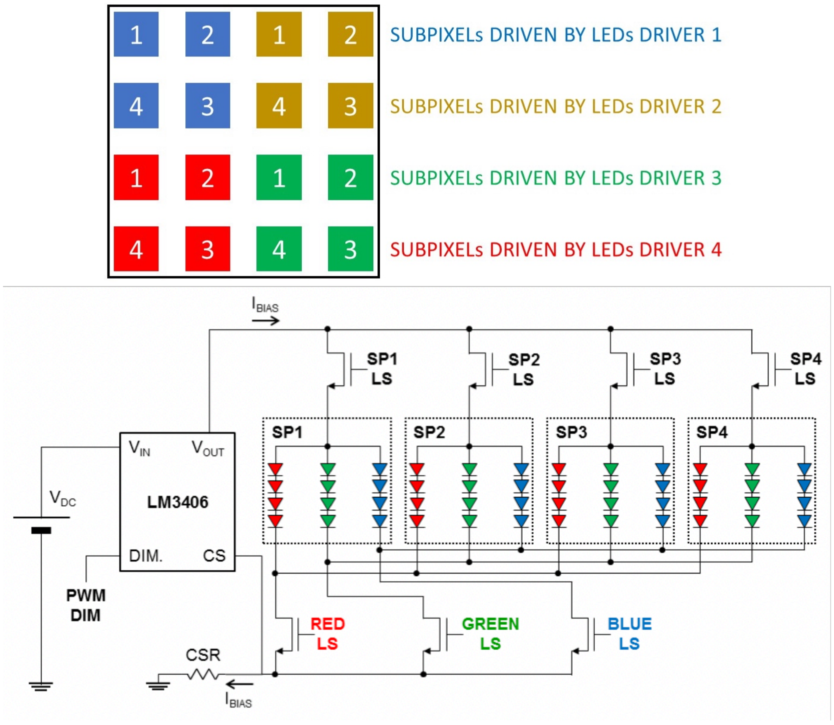


Figure 23. HDR approach, schematic assignment of the drivers (above) and block diagram of the driver architecture

2.3.1 Power consumption and efficiency

As already discussed, LUMENTILE™ was thought mainly as design appliance and a smart device to be installed permanently in public or private buildings. The light emission is only one function of the device itself, which is made unique by the ability of interacting with the user. The light emission is then wanted to be soft and pleasant, not bright and glaring as the one produced by a lighting fixture.

These choices at the high level of product definition have influenced the design, as it has been discussed already and will be discussed again later, with a direct implication on power consumption and efficiency of the device. Nevertheless, the proposed architecture and the optical structure presented later on are offering acceptable levels of power efficiency; reported in the table below.

	LDR tile	**HDR VIDEO tile**	**Stand-alone RGB LEDs - LDR**	**Stand-alone RGB LEDs - LDR**
Luminous power [lm]	556	346 (2945*)	1600	5300
Electrical consumption [W]	36	7.2 (69.3*)	30.4	101.3
Luminous efficiency [lm/W]	15.4	48.1 (42.5*)	52.6	52.6

* means "at full power"

The "Stand-alone RGB LEDs" columns indicate the theoretical maximum achievable with this approach. It can be observed that in the case of the HDR tile, where the light emission is not affected by any secondary optics but the protective polycarbonate cover, the efficiency is 81 to 91% of the theoretical maximum. In the LDR case, where the light is going through a secondary optical structure and through a ceramic top layer, the efficiency is 29.3%, which is also accounting for the power consumption of the electronics inside the tile.

3 Chapter 3: Light Guiding Layer

The light guiding layer, is the third one on the layered structure of LUMENTILE™. Its function is to manage the light emitted from the LED offering a uniform illumination of the surface, hiding the high intensity spots created by the LED themselves, without heavily affecting the efficiency in this process. As the name suggest, this layer is exclusively composed by a light guide, in charge of managing the illumination.

The light guide approach to manage the illumination intensity coming from LEDs or light sources in general is known since long time in the display technology. Although the challenges may seem similar, the requirements in the two cases are quite different.

3.1 Light guiding layer concept

The optical principle at the basis of a light guide is the refraction, explained by Snell's law [24]:

$$n_1 \sin\boldsymbol{\theta}_i = n_2 \sin\boldsymbol{\theta}_t$$

In case the light is traveling into a medium with $n_1 > n_2$ the transmission angle $\boldsymbol{\theta}_t$ is greater than the incidence angle $\boldsymbol{\theta}_i$. Accordingly to the refractive index values n_1 and n_2 of the two media, for a certain angle of incidence (called critical angle of incidence $\boldsymbol{\theta}_{crit}$), it corresponds a transmission angle equal to 90°. This value of transmission angles implies that no light is transmitted to the second medium, obtaining the phenomenon of total internal reflection (TIR).

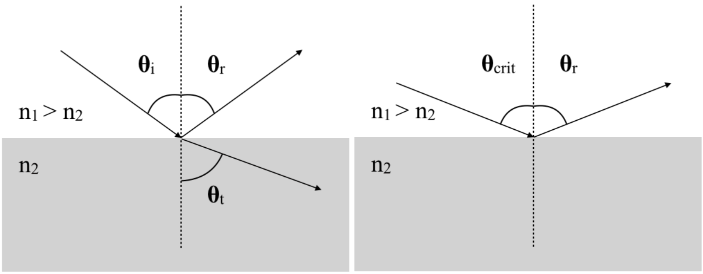


Figure 24. Snell's law and critical angle

Taking as an example the materials used for LUMENTILE™, the light guide is made by poly-methyl methacrylate (PMMA) which has a refractive index n_1=1.4906. The second medium would be air, with a refractive index n_2=1. With this value it results a critical angle of incidence of 42.13°.

Turning this angular value into a linear one, and anticipating the configuration of LED that will be described later, which sees the LEDs placed at 4mm height on the side of the guide, the total internal reflection appears at 3,5mm from the edge of the guide. Along this distance, the light is directly coupled outside the tile, both for the top and bottom faces of the guide.

3.2 State of the art

The high level design of any edge coupled LED based backlighting structure is:

- LED strip
- Light guide
- Light managing films.

The LED strip is usually made by tens of white LEDs, with a pitch dependent on image and system requirements such as operating voltage, area of the display, quality of the backlight, design of the screen. The illuminance pattern is highly dependent on the disposition of the LEDs behind the screen [25].

The light guide is usually made of a thin slab of PMMA or it consists is a volume left empty. In order to tune the illuminance and the brightness of the backlight, different films are placed below and above the light guide, over the whole area of the screen. The scope of them is to maximise the light extraction just from the top face of the guide. Hence, below the guide the films are used to improve the back-diffusion or reflection of light. This can be obtained with one or more sheets, white, or reflecting films. Above the light guide, the scope is to maximise the transmission, and in case of displays, regulate the viewing angle to obtain the desired brightness in a preferred direction (the user is always in front of the screen). These types of film are called brightness enhancement films (BEF) and are made by microstructures, usually prisms [26]. Above this, an additional film can be placed with the scope of increasing the uniformity of the backlight. The diffusing films are built with scattering structures, diffusing the light in multiple direction according to the shape of these scattering centres. The addition of these films is increasing the diffusion of light inside the light guide, obtaining a more uniform illumination [27].

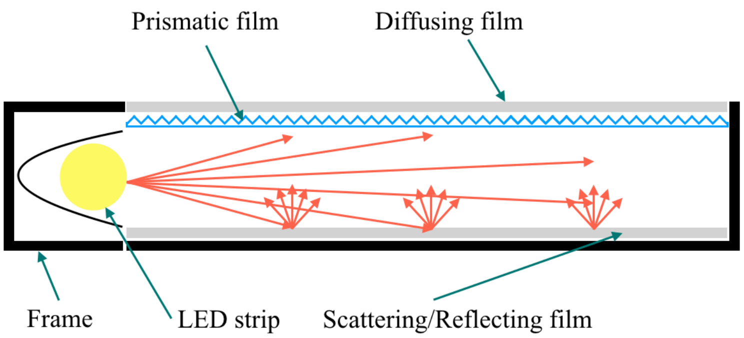


Figure 25. Films and light guide stack in an edge lit backlight system

3.3 LUMENTILE™ solution

Although the challenges in the display technology solution and LUMENTILE™ are similar, there are many key points differentiating them. The differences in the problem of designing a backlight illumination system for displays and for LUMENTILE™ are mainly two.

The first comes from the mechanical resistance requirements asked to the tile. The light guide in LUMENTILE™ is a structural component, and as such, it needs to be solid and able to bare heavy weights, since it will be installed on floor and stepped on continuously.

The second is linked to the visual requirements for the tile. The idea is to have a surface which is entirely coloured, with no dark areas, and most importantly with no frames. The whole area of the tile needs to be illuminated. This requirement, from an optical design perspective is really restricting.

Any edge lit display has in fact a black (or opaque) frame which function is to cover the strip of LEDs and an area of the light guide called *mixing zone*. This zone is right in front of the LED, where their light is coupled to the light guide. It corresponds to the distance necessary for the light of the single emitters to mix with each other.

Moreover, if the face of the light guide on which the light is coupled does not have a smooth finish, some scattering centres are creating secondary sources emitting over a Lambertian solid angle. Since this zone is close to the source position, below the length needed to achieve the TIR, all the light in this area is directly coupled outside of the guide, without actually getting the light guiding effect.

For all these reasons, a great fraction of the light emitted by the LED is directly coupled to the top surface, generating *hot spots* in the illumination pattern. This gives really bright areas, where the light intensity is much higher compared to the rest of the surface.

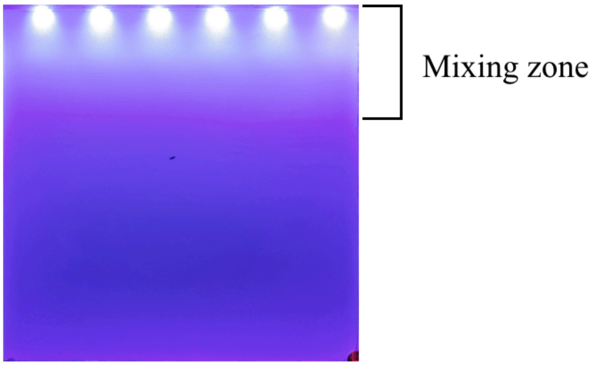


Figure 26. Figure showing the hot spots created in the light guide

3.4 LUMENTILE™ light guide structure

The light guide for LUMENTILE™ needed to be a bulk and solid structure, the best option was thus to have a single slab of material, with the same sizes of the available volume inside the tile (286mm x 286mm x 8mm), giving a hard support for the load the tile is demanded to sustain.

The requirement of having four well separated quadrants (or pixels) inside the tile is on the other hand asking for optical barriers between the quadrants; meaning that the single slab cannot be an option, but an approach with four of them separated, manufactured and successively installed together needs to be used.

Another aspect to be considered in the design of the light guiding layer for LUMENTILE™ was the simplicity of the component. This is both affecting the material cost and the assembly phase complexity. For this reason, the goal was having, in the best scenario, a single component, easy to install in the tile during the assembly process. This meant reducing at minimum the use of additional films above or below guide, which has to be designed so that the component is guiding the light itself, and diffusing it in a uniform manner over the whole area.

Since the tile is divided in quadrants, the light guiding layer is effectively 143mm x 143mm large and the thickness is exploiting the whole available height.

A note is worth to be added here about the thickness. The ultimate goal of the project was to develop a 16mm thick tile, with 20mm being a more realistic target to achieve. With 20mm, the maximum height reserved to the light guiding layer is 8mm. Also for this reason, the only choice for the backlighting configuration was the side coupling, offering the possibility of illuminating uniformly a surface easier than the direct coupling backlight when the guide thickness is reduced.

The LEDs identified for LUMENTILE™, as discussed in chapter 3, are surface mount technology (SMT) devices with sizes 1.3mm width, 1.7mm length, 0.7mm height. To minimise the thickness of the light guide then, the three LEDs needed to be installed one next to the other in line, coupled to a light guide 2mm thick.

This approach was giving though an annoying effect in the early stages of the project, because right over the LEDs (recalling that no frame is foreseen in LUMENTILE™) the colours were not mixing with each other, giving primary colours spots when creating light over the tile.

Figure 27. In line placement of the RGB LEDs triplet and the resulting separation of primary components over the tile

Placing the LED stacked vertically, is increasing the thickness of the light guide, which thus has to have a minimum height of 1.7mm x 3 = 5.1mm.

Stacking the LEDs would thus solve the problem of the colour separation at the edges, but the thickness of the light guide would be too much if considering the tolerances required by the ceramic parts and the tolerances to take into account during the assembling phase. The light guide thickness was thus set at the maximum, 8mm, with the LEDs placed as in the previous figure. The colour mixing problem was thus to be solved during the project development.

The final structure of the light guiding layer is hence made of four separated pieces, consisting in slabs of PMMA. The four slabs are identical; each of them is illuminated with six light sources (with source here is intended a RGB triplet) with a resulting pitch of 24mm.

As we said before, the surface of the tile needs to be without any frame, and so it needs to be the the light guiding layer. Placing the light sources inside the screen area, with a side coupled backlight is very challenging because of the effects explained before, creating hot spots. This requirement is important for LUMENTILE™, but not needed in the display field, thus a defined approach to solve the issue was found.

An additional structure detail is needed to reduce the back scattering created in the coupling process. The best approach would be to create a sort of optical element coupling all the light emitted by the LEDs, over the whole emission angle, inside the guide, this can be done with a hemispherical window in front of the LEDs.

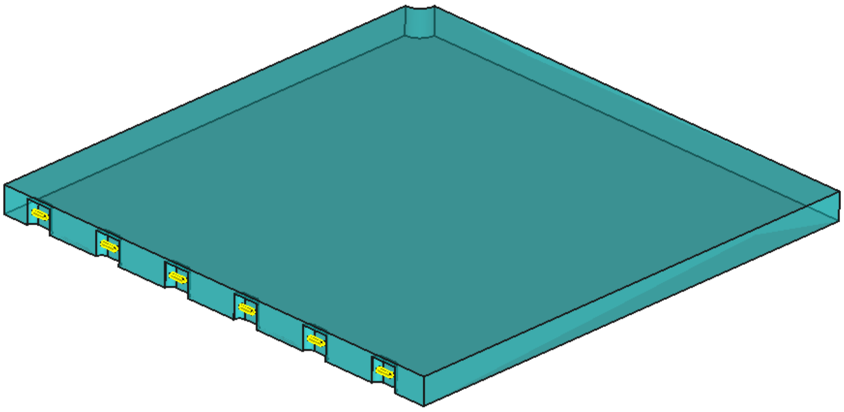


Figure 28. Light guide with the windows on the side for better coupling

Obtaining this trenches in a block of PMMA is though not possible with the standard cutting process. The PMMA is usually produced through extrusion in very large panels of several square metres and then cut into the desired shape. To have additional features, it is necessary to produce the PMMA with a moulding process and the much higher cost of this option required an alternative solution for the prototype production in the scope of LUMENTILE™ project.

The greatest contribution to the hot spots is created by the direct coupling of the light from the LEDs to the top layer, given by the large emission angle of the LED and also caused by the reflections at the first interface with the light guide. To solve this, a viable and not expensive solution was to create an overlay on the side of the light guide, right over the LEDs.

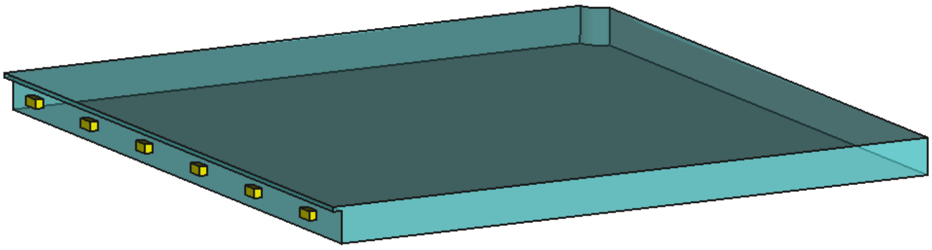


Figure 29. Light guide with the overlay on the LEDs

This cover on the LEDs allows to decrease the hotspot intensity.

Without considering the hotspots, the light intensity on the top surface of the tile has a decay proportional to the inverse of the distance from the light source. To balance the intensity at an average value over the entire surface, obtaining uniformity, the light guide layer must ensure an opposite trend of light extraction.

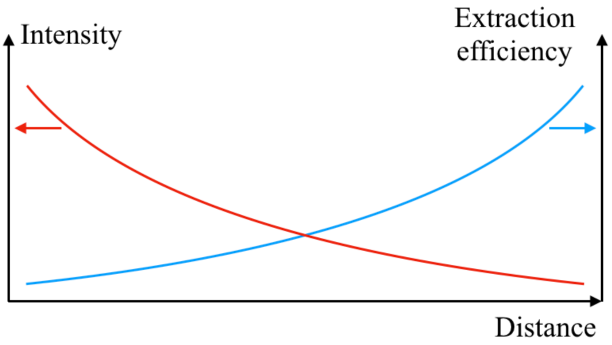


Figure 30. Basic concept of the extraction efficiency of the light guiding layer for a uniform illumination

To obtain this effect, and at the same time, reducing at minimum the number of additional components to be used in the light guiding layer, the idea was to create a pattern directly on the faces of the light guide.

The pattern is created over both the faces of the light guide. On the top face the patter has the function of blocking the light to exit the guide, sending it back inside the structure. On the bottom face on the other hand, the pattern has the function of adding scattering centres, so that the guiding effect created by the TIR is interrupted. This scattering centres are thus diffusing the light towards the top face.

The creation of the patterns is done through an algorithm written in Matlab™. The first step is analysing the illumination over the surface of a clean light guide. This can be easily done by taking a photo of the light guide illuminated with the six LEDs and without any other components helping the uniformity.

The image is then analysed with the Matlab™ script, in order to identify the local light intensity over the top surface. An example of the data displayed as a heat map is reported in the figure below.

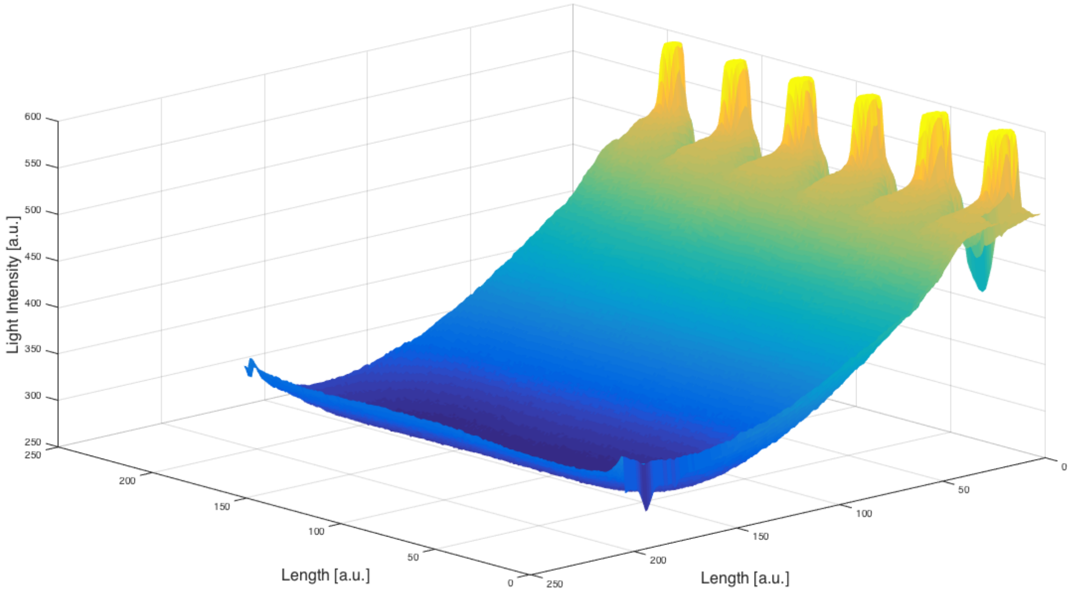


Figure 31. Light intensity heat map over the surface of the light guide

Once this distribution is obtained, the patterns are created to balance the local light extraction. The blueish zones in the figure will require a high extraction efficiency, the yellow zones need to be dimmed down with a lower extraction efficiency and higher power attenuation.

The resulting grids are like the one reported in the following figure. The patterns for the top and bottom face are identical in their details, but opposite in their values: where the top has a feature to block the light and send it back in the guide, the bottom one doesn’t have any feature to allow the total internal reflection.

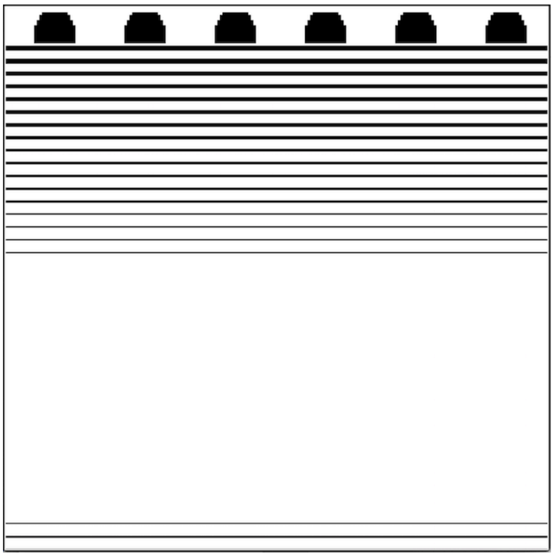


Figure 32. Example of a pattern controlling the light extraction

The illumination, and thus the extraction efficiency patterns are described by a continuous function over space, but for the manufacturing process, it is easier to translate the continuous pattern into a discrete one. The discrete pattern is thus characterised by smaller areas with the function of reflecting, absorbing or scattering the light.

The shapes of these areas can be different. In the figure above it is reported a grid made with a mix of wider and thinner lines, with local black dots. The larger black zones at the top of the figure are corresponding to the hotspots created near the LEDs.

Under an optical point of view, these areas are controlling the local refractive index, and consequently reflection coefficient of the guide-air interface, in order to control the total internal reflection and diffusion in each point. The total internal reflection is controlled by changing the refractive index of the second medium, out of the light guide. This has been done in different ways.

Laser milling

First, a layer of reflective material is deposited over the faces of the slab with a sputtering process. The coating is then selectively removed by a laser beam. This solution is the most precise because it offers a high precision in details, below 100µm, but the costs are too high to be implemented in an industrial production over a large scale.

Ink Jet Printing

The grid as depicted in the figure above is printed digitally on the faces of the light guide with a standard ink jet printing process where the extraction details are defined with black and white inks. This solution is much more advantageous in terms of costs and production wastes. However, the minimum achievable transmission is too high to eliminate the hotspot created by the LEDs and the losses introduced by the black paint are too high. Moreover, the ink used to print on polycarbonate showed a destructive chemical interaction with glues during the assembly, compromising the final quality and integrity of the print.

Lithographic Painting

This last approach consists in painting the grid on the top face with white gloss. The bottom is completely painted with white, the extraction is then controlled exclusively on the top face. The surface is painted through the use of a mask, which design is consisting in filled or empty areas. This allows to finely tune the light transmission through the top face. On the bottom face, the paint can be removed below the zones corresponding to the hot spots in order to reduce further their intensity.

This manufacturing approach has been the one offering the best results. A good level of uniformity was reached, the figure below is showing a comparison of the light guide with and without the pattern on the top face. Additionally, this approach is offering a good scalability for the larger areas foreseen in the production, and the production cost is low, consisting only in buying the paint necessary for obtaining the pattern.

In LUMENTILE™, there is no additional film added on the top of the light guide, like BEF or diffusers. The diffusing effect is enhanced by the availability in LUMENTILE™ of a top layer, made by either glass or ceramic. This is helping the diffusion of light and allowing the use of discrete patterns on the top surface, which would be otherwise visible without the top layer. The action of this latest is though just smoothing locally the intensity without being able to tune efficiently the light distribution over larger area.

The figure below is visually showing the final results, together with a heat map similar to the previous one. It can be seen that the intensity of the hotspots is greatly reduced, and the uniformity over the remaining area is increased.

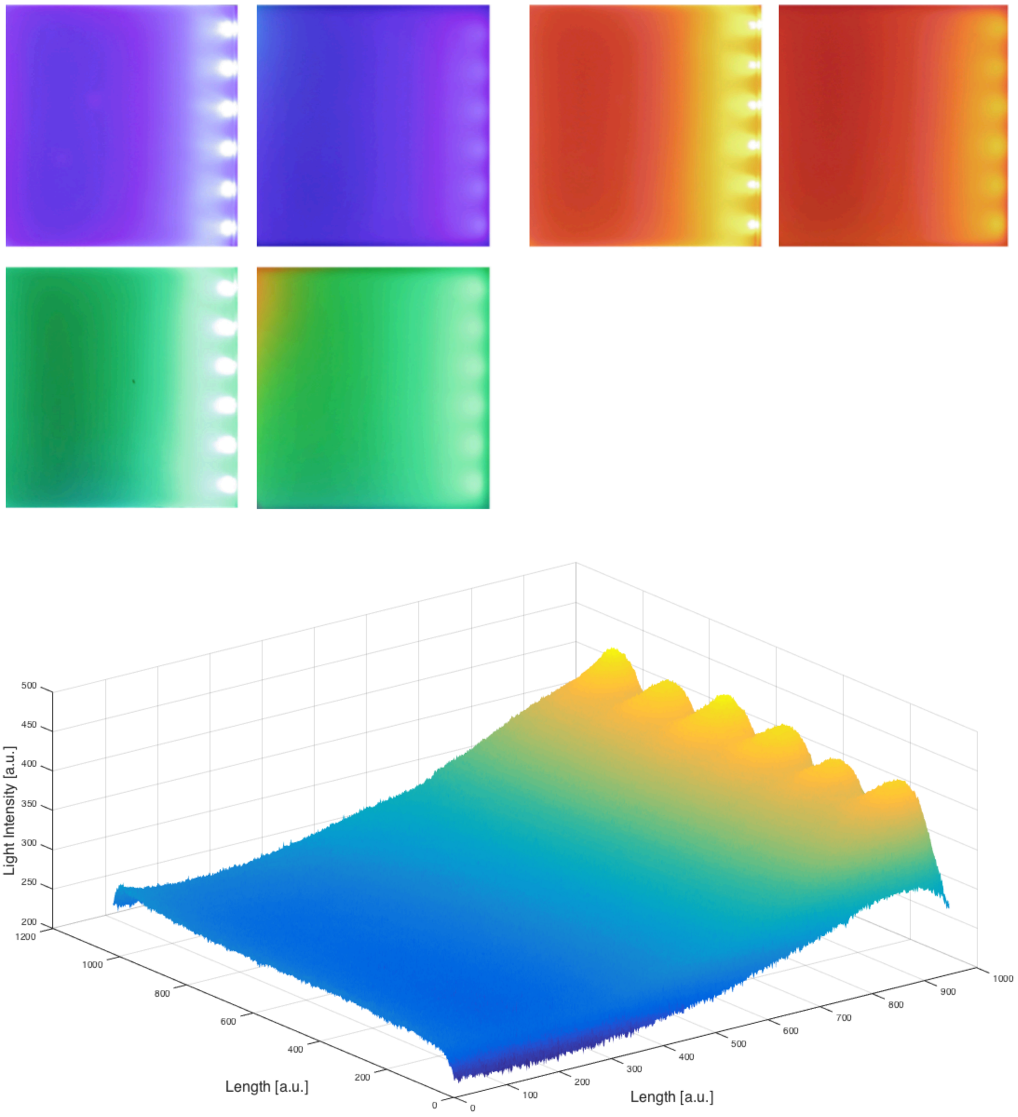


Figure 33. Light guiding layer comparison with and without the top grid

The last phase of the work on this design of light guiding layer was focused on increasing the coupling efficiency.

The light guiding slabs described so far had been manufactured by cutting a larger piece of material with mechanical saw tooling. This process creates a rough surface on the side of the light guide. This surface, when coupling the light to the guide is enhancing the scattering and thus the hot-spots intensity. To overcome this problem, a different method of cutting can be used.

This cutting process is done with a hot blade dividing the larger piece of PMMA and this melts the material, giving a clear and smooth side face. The downside it that this approach doesn’t offer the possibility of creating any 3D details during the cutting, meaning that the cover of the LED cannot be created, giving glares on the borders due to the reflections of the coupling process. The hotspots inside the light guide are though greatly reduced, giving a more uniform illumination if the frame is ignored.

Figure 34. Light guiding layer with a smoothed side face

3.5 Light guiding layer for 2D PCB

The light guiding layer structure presented in the previous section is presenting some drawbacks.

The edge-coupling concept calls for a maximum size of the individual LDR tile containing four pixels at the maximum with side of ~150mm. The tile size is limited by the fact that the LEDs must be located in the vicinity of the vertical edges of the bottom, for heat dissipation purposes, and for the mechanical stability of the LED-to-slab coupling.

The industrial assembly process for this configuration is not straight-forward because of the tolerances on the horizontal position of the LEDs. As a consequence, a variation in the LED-to-slab distance will cause optical losses, increases in the hot-spots intensity and illumination non-uniformity between slabs within the same tile, and also from tile to tile.

The edge-emitting configuration poses constraints on the electronic PCB, which must be a 3D structure. In fact, as described previously, the light sources PCB that carries the LEDs needs to be mounted at 90° with respect to the plane of the main PCB, through connectors soldered onto the main PCB. This brings additional material cost, and also adds an additional step in the industrial assembly process.

Another problem arises with the occupied area. With the LEDs installed along the frame of the tile, the current needs to be brought at the borders of the tiles, requiring then a large area PCB or additional, unwanted, cabling.

To overcome these problems, two new designs were proposed for the light guiding layer with a common basic concept, the conjugation of planar and edge configurations.

The light sources are placed as in a planar configuration, on the same plane of the top surface. Their distribution though is not uniform over the plane but exclusively along the frame. The light emitted is then collected by a light pipe which is transporting the light into the actual light guide to spread the illumination over the surface. In this way it is possible to combine the installation advantages of the planar backlight, with the performances of the edge configuration over reduced thickness.

The resulting structure has a L-shape and is illustrated in the figure below.

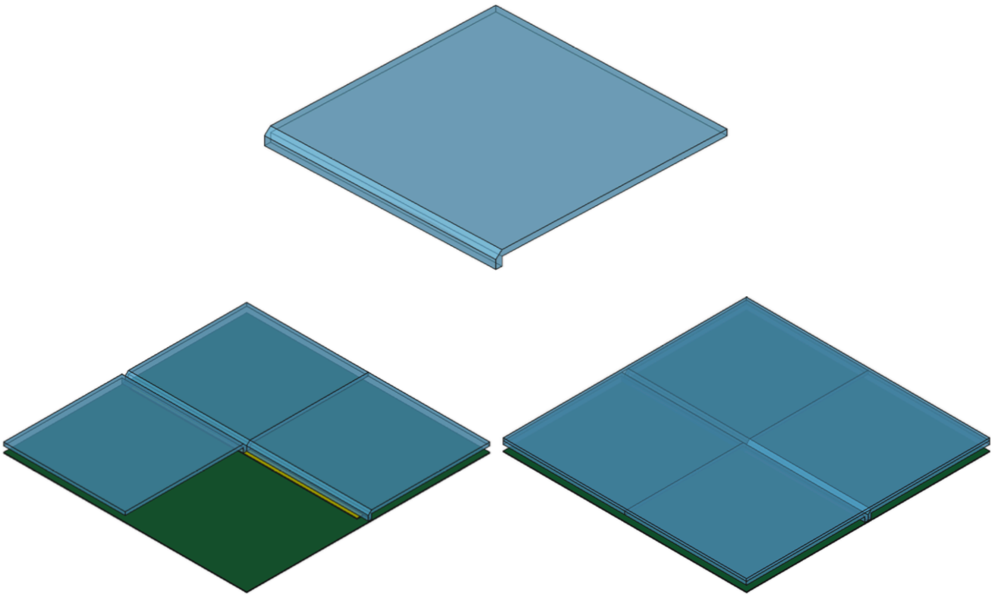


Figure 35. "L-shaped" LGL.

The LEDs stripes are represented by the yellow bars, positioned horizontally onto the PCB. Assembly into a standard 4x sub-pixel tile configuration is shown.

The guide is made by a coupling light pipe collecting the light emitted by the LEDs, then a 45° mirror is reflecting the light inside the main part of the guide, where a process analogous to the one presented in the previous section is made, controlling the extraction efficiency from the top surface.

This concept simplifies both the design of the light source layer and the assembly phase, reducing the costs of this two. The industrial assembly process for tiles using the "L-shaped" LGL will be highly simplified, because all assembly steps will involve planar layers/objects. Moreover, the LED-to-slab coupling efficiency will be higher and highly repeatable, thanks to the high precision in the relative vertical placement of the LEDs and the coupling edge of the "L-shaped" LGL. The PCB can be produced in a more standard shape and also reduced in size, reducing the production costs.

Another important advantage of this solution is its scalability in size. The removal of the light source PCBs on the sides means that the bottom layer is not constrained anymore to be 300mm x 300mm to offer a sustain to the board but can be larger in sizes according to the demand of the user. To be noted that in tile installation the demand in the latest years is asking for panel up to 600mm x 600mm or 600mm x 900mm.

4 Chapter 4: Gesture Sensing System

Both the LDR models in LUMENTILE™ are embedding sensing system in order to interact with the user. The possibility for the tiles to detect an external solicitation and react accordingly, sharing data with the outside is what makes the LUMENTILE™ a smart device.

The Wall tile, installed on vertical surfaces, at the same height of human, can interact with the users through sensors detecting the movement of an arm or a hand, waived in front of the tiles wall. The Wall Tile is requiring a system not only able to sense the presence of the user in front of the surface, but it should also provide different responses to different movements of a waving target over the tile. For example, being able to identify basic types of movements, like: i) sweeping a hand from left to right (and vice-versa); ii) sweeping a hand from top to bottom (and vice-versa); iii) moving a hand from far away towards the tile (and vice-versa). This, the combination of the sensing system and the CPU shall turn the tile into a gesture sensing system.

4.1 Gesture requirement

The interaction specification defined for the gestures detection were requiring the ability for the system to discriminate the movement along three axis over the tile, reported in figure using cardinal references.

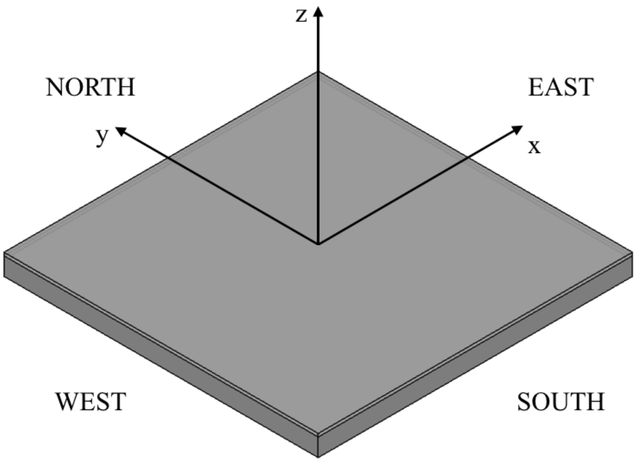


Figure 36. LUMENTILE™ with cardinal references

The sensor needs to be able to distinguish movements along these lines in both directions. This means that the system should discriminate North to South movement and South to North for the y axis for example, and the same is for the other axis.

Another requirement was that the sensor needed to operate in a contactless situation. This type of interaction is thought to be more appealing, also, since the device can be installed in public spaces where more people can interact with it, the contactless operation can be beneficial both in terms of hygiene and to reduce at minimum the degradation characteristic of a touch based system.

For this reasons a standard touch sensor based on capacitive or resistive systems cannot be considered.

4.2 State of the art in gesture sensing

The market is offering a number of different solution targeting the contactless gesture discrimination. The *gesture* itself is usually derived from a primary physical phenomenon. With electromagnetic waves it can be interference, time of flight measurement, phase shift or change in a sustained electromagnetic field.

These commercial devices can be divided according to the operational principle:

- Optical sensors: based on infrared and near infrared light interaction
- Microwave: based on Doppler effect with radiations usually in the X-Band[1]
- Capacitive: based on sensing the change in field created by two capacitive plates.

Among these, the most flexible and precise type of sensors are the optical ones. They can be further divided into passive sensors or active ones.

The passive sensors, operating in the infrared (PIR, passive infrared sensor), are based on the detection of thermal radiation emitted by an object entering the field of view of the sensor [28]. Every low cost motion detector (alarms or presence based automatic lighting system) is based on these type of detectors. Anyway, they are offering a digital-type signal: presence or absence of an object with a specific temperature in the field of view. More of them can be used together to get a discrete definition of the surroundings, but their sensitiveness to any heat source make these sensors unreliable for a precise measurement.

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[1] With X-Band it is commonly intended the range of frequencies in the microwave region from 7 to 12GHz.

The active sensors are made by a transmitter and a receiver. The radiation is emitted, it interacts with the object, and collected by the detector. These sensors are usually based on near infrared light, where a light source, LED or laser is used as an emitter and a photodiode, usually based on silicon, is used as a receiver.

Since the electromagnetic emission is in the order of 400 ÷ 500 THz, the simplest quantity to be interpreted in the process is the time of flight. Time of flight sensing systems (ToF) are well known in the metrology landscape. The basic principle is to measure a time delay occurred for a light ray travelling from the emitter, being scattered by the target and reaching the detector. The time delay, knowing the properties of the medium in which the radiation is travelling, gives information on the path length, and thus the object distance. These type of sensors are really common and can be also found in mobile phones, where are used to dim down the intensity and deactivate the touchscreen when an object is too close to the device, meaning we are not really using the screen, e.g. our face during a call, or the inside of a pocket or bag.

4.3 LUMENTILE™ solution

4.3.1 Use-case scenario and principle of operation

LUMENTILE™ is requiring a hidden gesture detection system, meaning that from the external face of the tile, nothing should be suggesting the presence of a sensing system. The top of the tile though, is either made by ceramic or glass covered with coloured enamel, i.e. an opaque material. The flexibility and well established technology in the time of flight sensors make it a good candidate for the application. Nevertheless, when installing a time of flight sensor inside the tile, the non-transparency of the upper layers is thus causing back scattering of the light emitted and a false read by the detector, which is collecting the light backscattered by the top layer, ignoring the light scattered by the object (a hand) in front of the tile and giving a response also if there is no object to be detected.

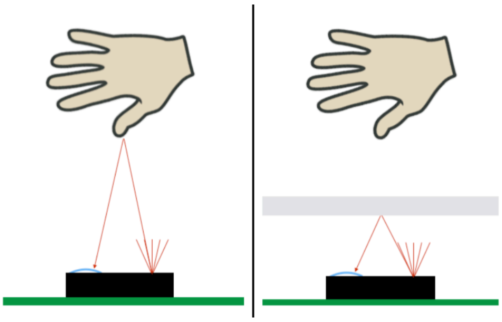

Figure 37. False reading example of the integrated ToF

This issue is due to the fact that the market needs are asking for smaller and smaller devices, thus in the commercial integrated ToF systems the size is a primary aspect and the detector and emitter are placed very close to each other [29, 30]. When the sensor is then integrated into the main device a window is created, avoiding this false reading.

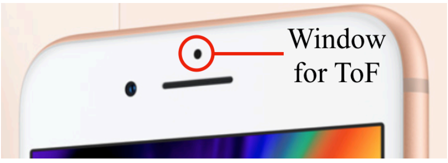

Figure 38. Window for ToF sensor in a mobile phone

This solution of creating apertures in the top layer is not viable for LUMENTILE™ because as said earlier, the requirement is a perfectly uniform surface with no defects, even small holes acting as windows.

The solution for this problem has been to create a bespoke gesture sensor based on scattering from an object waving over the tile, which is not affected by the presence of opaque layers with different refractive indexes, causing back reflections, along the optical path from the emitter to the detector.

The idea is based on optical triangulation: the object position in every instant in time is determined through the measurement of the relative delays in the responses recorded by different detectors positioned at known points. In an optical based scenario, the detectors are photodetectors, sensing the light, emitted by a single LED and backscattered by the target. For LUMENTILE™, the target is a hand, the LED is an infrared LED [31] placed in the very centre of the tile and the detectors are four pin silicon photodiode [32], arranged in a cross shape along the main axis of the tile.

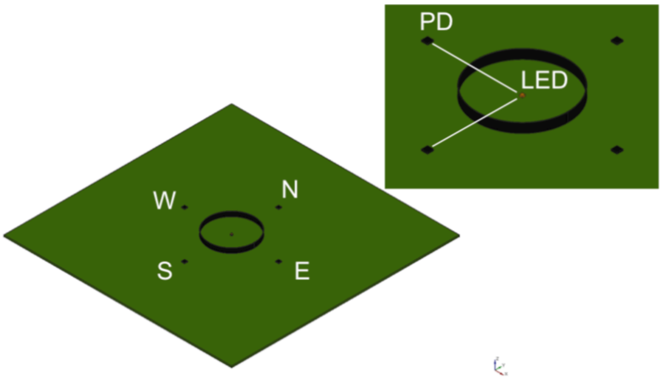

Figure 39. LED and Photodiode (PD) placement in the tile area

The figure above is reporting the arrangement of the five elements on the main PCB. Together with the optoelectronic devices, a black ring is placed around the LED. This ring has the scope of preventing the direct back-reflections of infrared light from the LED towards the photodiodes. The effect of this reflection can affect the correct functioning of the system, saturating the photodiodes. Large fraction of the emitted light is in fact blocked by the layers above and scattered back inside the tile. Fitting the ring is preventing this scattered light to reach the photodiode, hence improving the signal to noise figure of the system, this effect can be reached also without fitting the ring, but the LEDs and the photodetectors need to be spatially separated by few centimetres. 5cm is the distance used in the current design, the maximum allowed by the bottom structure and main PCB layout.

The functioning of this system is based on the intensity of the portion of infrared light emitted by the LED and reflected back by the target towards the photodiodes. By detecting changes in amplitude of the signals acquired from the photodiodes and delays occurring across them, the relative position of the target over time can be determined. The sequential steps of the gesture detection process are illustrated below:

1. After the sensing system is activated, the LED is driven with a defined frequency alternate current. The four photodiodes convert into current every light contribution falling in the field of view. This means a noise floor in defined by a DC and a AC component. The DC can be due to sunlight, AC components at different frequencies are due to ambient lighting. Apart from this, also an AC noise component, at the same frequency is generated. This is due to the IR light leaking from the layers above the LED and reaching the photodiodes (see figure

below). The black ring is acting as an optical barrier reducing the diffusion of the scattered light at the PCB level.

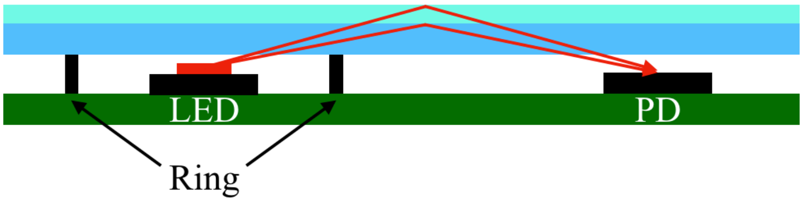

Figure 40. Illustration of guided light trough the upper layers towards the photodiode

2. The target (users hand) enters the field of view of the LED. The light is the back scattered toward the photodiodes. An additional AC component is then created by the photodiodes front ends.
3. This additional signal component is the signal related to the gesture, and the one to be detected by the system.
4. If the hand is moving over the tile, the signal given by the photodiodes are changing in amplitude over time, proportionally to the distance LED - target - photodiode. The shorter this path, the higher the quantity of backscattered light, the amplitude of the photodiodes.
5. The four responses coming from the photodiodes are then sent to the microprocessor which analyses the signal in amplitude, and its changes over time. The delays between the responses and their amplitudes, identifies the position of the object during a certain acquisition period and can then translate this into a movement pattern of the hand, giving a dedicated response for every movement.

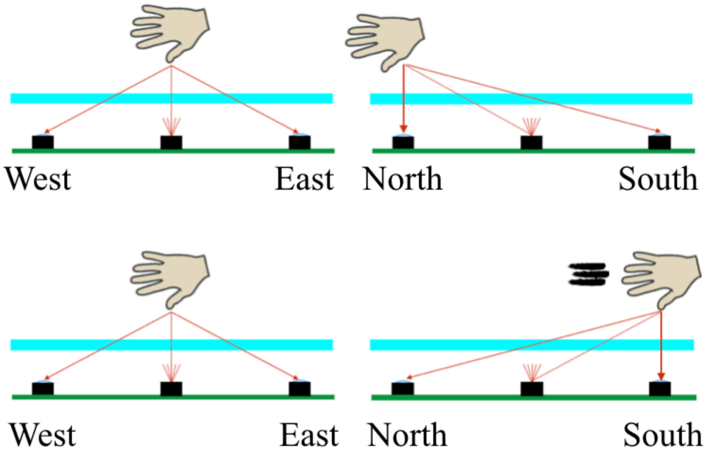

Figure 41. Example of a gesture to be detected by the system. The following figure is reporting the corresponding response given by the photodiode vs time.

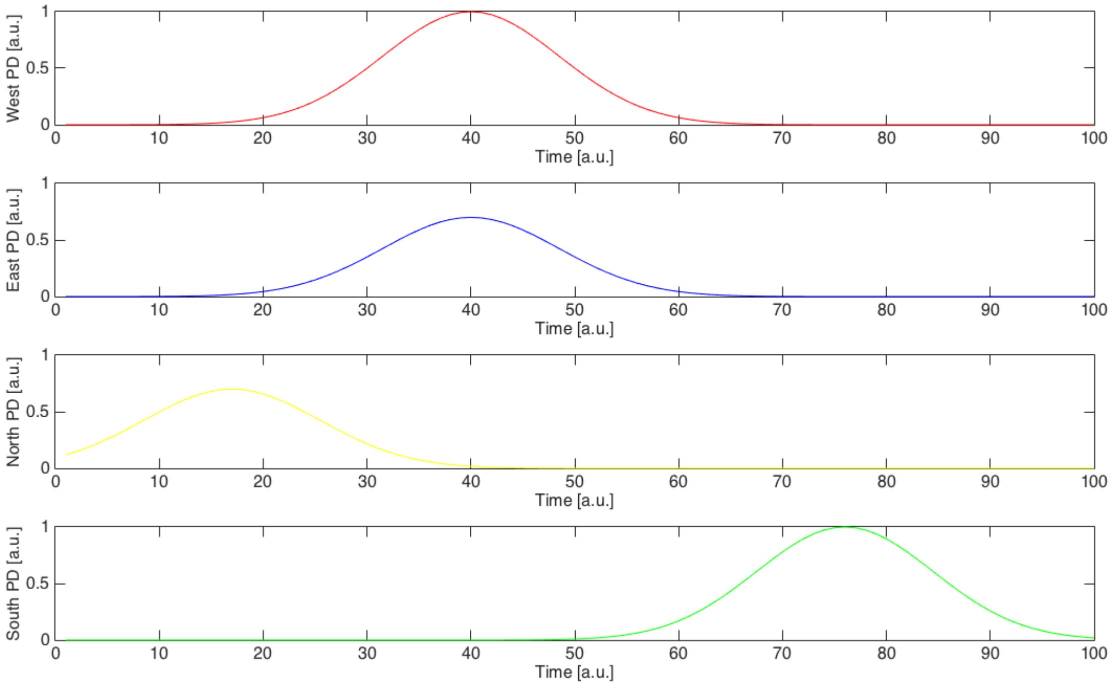

Figure 42. Response of the four photodiode to the previous gesture versus time.

The movement is going North to South, this means that the North photodiode is giving the earliest response, followed by the two East and West photodiodes (which give a weaker response since they are further away) and at last the South photodiode is giving its response.

To every movement is corresponding a response in time of the four photodiode. As an example, a movement on the plane will create a similar response to the one described in the figures above, if the movement is following the normal axis, towards the tile, all the four photodiodes will give the same synchronised response.

The amplitudes of the signals are directly related to the vicinity of the object and its reflectivity. The time durations of the pulses reported in the figure above are linked to the movement speed, the shorter is the pulse in time, the fastest is the movement generating the response.

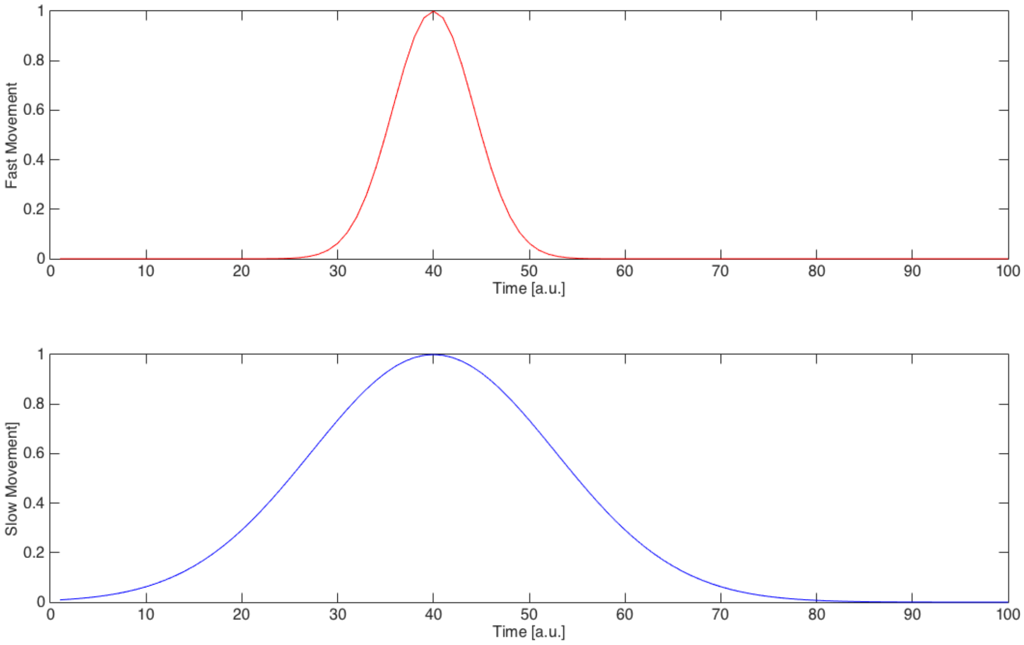

Figure 43. Time diagrams of responses for a slow movement (below) and a fast movement (above) responses

4.3.2 Readout circuitry design and implementation

The circuit implementation to obtain this behaviour is described here below.

Emitter

The LED is supplied with an alternate current. The current is obtained with a basic voltage to current stage formed by a n-MOSFET. The gate of the MOSFET is driven with a square signal with amplitude 3.3V. This is a logical signal coming from the microcontroller. The average power emitted by the LED is 30mW, 5mW are then eventually delivered through the ceramic top layer to the outside.

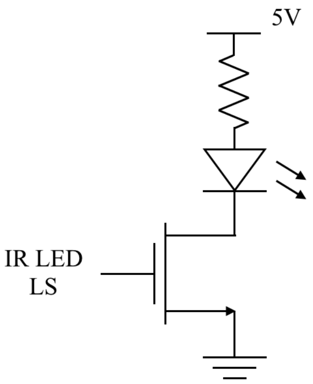

Figure 44. V2I Infrared LED driving stage

The frequency of the signal is set to a value between 600 and 900Hz. The frequency is assigned to the tile during the configuration phase of the wall installation. It is set different in order to avoid interference between adjacent tiles. The detection is in fact based on a homodyne scheme, as it will be described in the next paragraphs. The assignation of a defined driving frequency to a tile is done following the scheme reported in figure where $f_{1\text{-}4}$ indicates the driving frequency of the IR-LED.

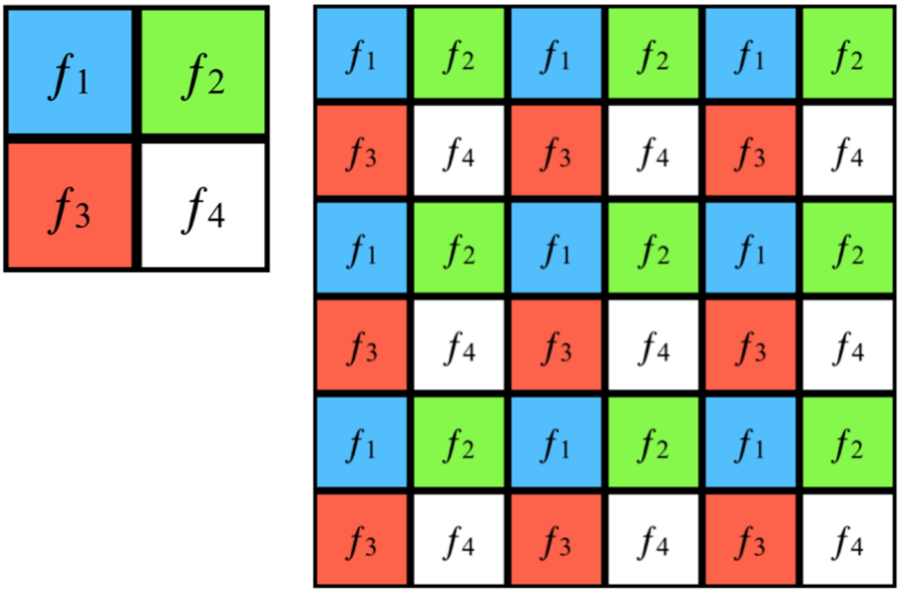

Figure 45. Frequency assignment procedure for the gesture sensing system LED

The analogue front end for the four photodiodes is exactly the same and it is composed as follows:

- the signal from the photodiode is AC coupled to high impedance amplifier, acting as a gain and bandpass filtering stage. The cut on frequency is allowing to eliminate sunlight contribution and low frequency signals (ambient light at 50-60Hz); the cut-off frequency is set to 10kHz to delete the higher frequency noises like ambient light with LEDs and, most importantly, the LEDs embedded in the tile itself
- an coherent receiving stage is then isolating the signal at the frequency of the LED. This is the only frequency the detection system is interested in analysing
- a low pass filter at 30Hz is then giving an average low frequency signal to provide to the analog to digital converter inside the microcontroller.

The block diagram illustrating the chain is reported in the figure below.

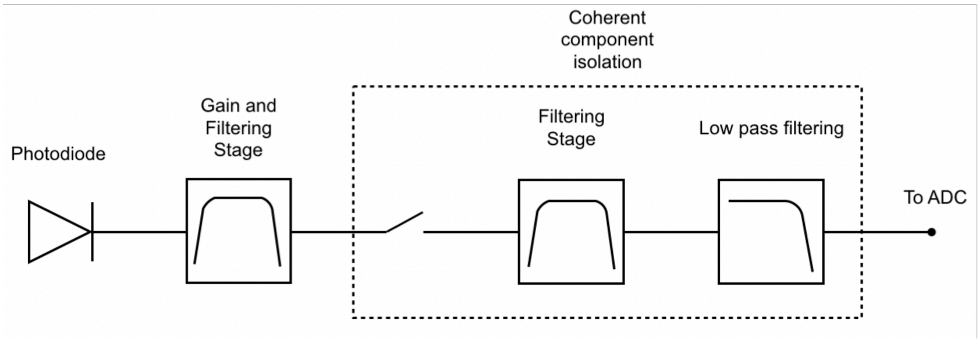

Figure 46. Block diagram for the receiver front end of the gesture sensing system

The homodyne detection is obtained with the second part of the receiver. The idea is the following:

- the signal in output (V IN) of the first stage is a square wave (with the same frequency to the one driving the LED) with amplitude V_p and average $V_p/2$
- this signal is then AC coupled to a common mode voltage of 2.5V (V 1). The resulting signal is a signal with the same amplitude with the average shifted at 2.5V
- a switch (MOSFET) and an an amplifier are then creating a stage with a variable gain of +1 and -1 switching at the same frequency of the signal (GAIN). The square signals at this same frequency and synchronised with the switch are thus creating a DC signal at $2.5 \pm V_p/2$ according to the switch logic; the signals at different frequencies are giving instead an AC signal with a 2.5V average. This voltage is then passed through a low pass filter at very low frequency (30Hz) which has the only function of extracting the average. If the signal has the same frequency of the LED, the contribution is $V_p/2$ (V OUT); otherwise if the frequency is different or the signal is asynchronous, its average is null giving then an output at 2.5V (Async. Sig.).

We should notice that the previous is true only for periodic signals.

The figures below are reporting the schematic and the signals at the various stages.

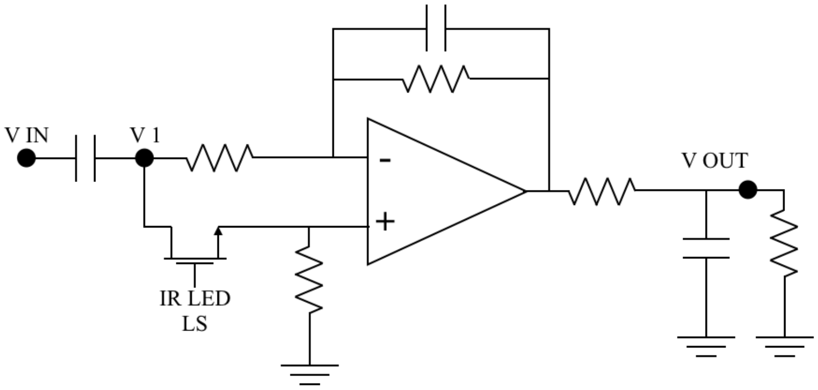

Figure 47. Schematic of the receiver homodyne detection section

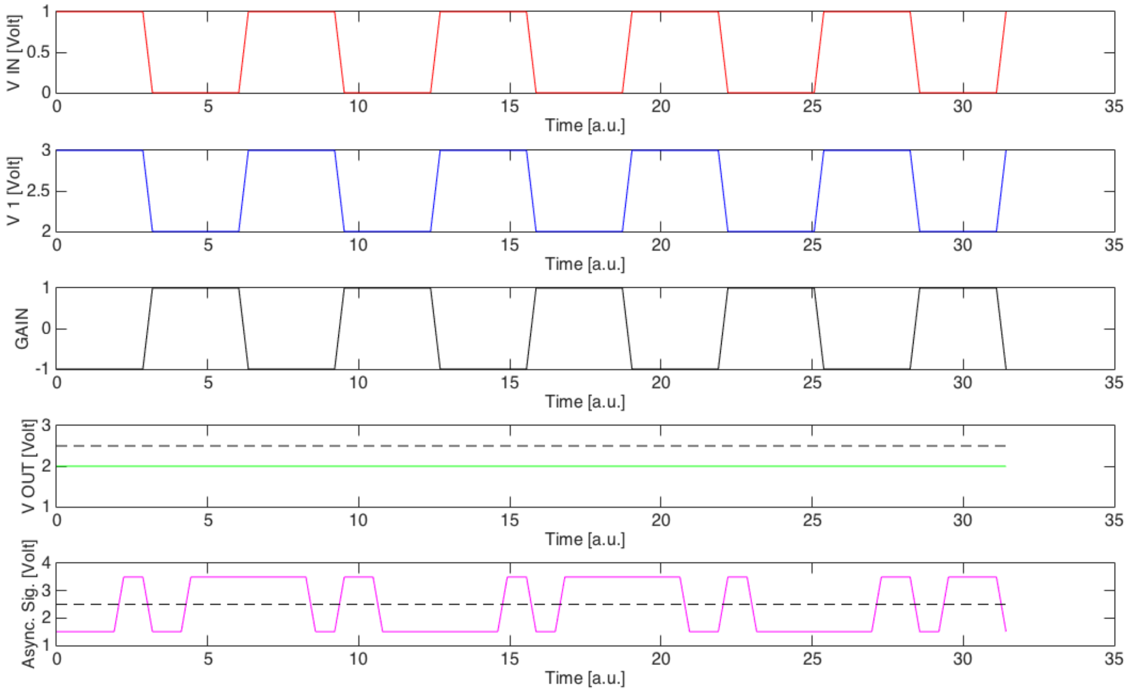

Figure 48. Signal curves vs time of the signals involved in the homodyne detection

4.3.3 Results

The described system was tested and installed in the actual tile. The sensing system showed full functionalities up to a distance of 10 cm from the tile surface when the top layer was glass, and 3 to 5 cm when the top layer was ceramic. Some curves representing the outputs of the receiver, before the ADC is reported in the figures below.

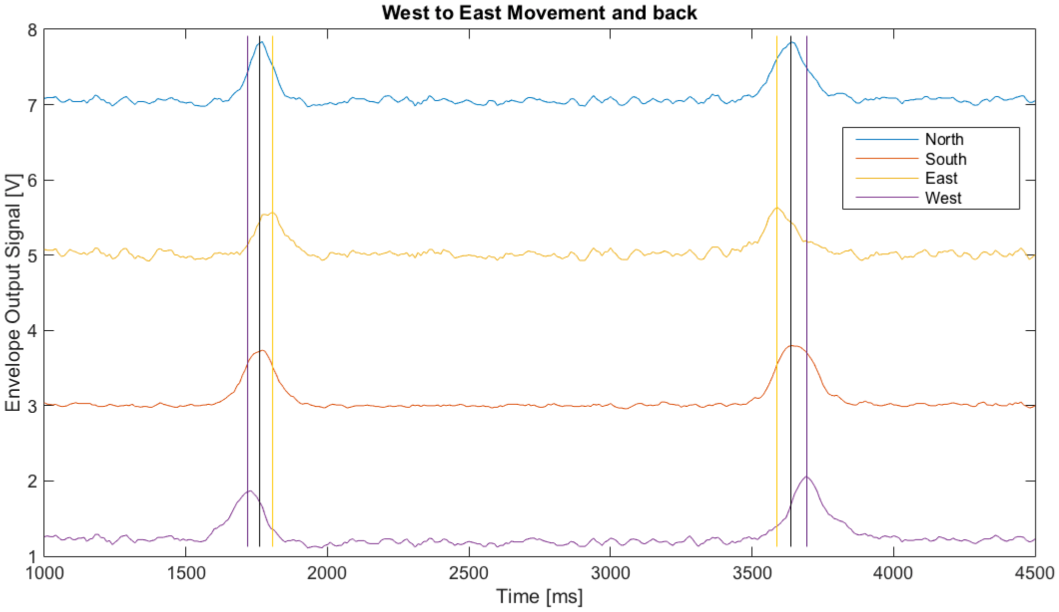

Figure 49. V OUT curves in time of a movement from West to East and back over the tile surface.

It can be seen how the West photodiode signal precedes the others with the East photodiode signal being the last on the left part, and vice versa on right

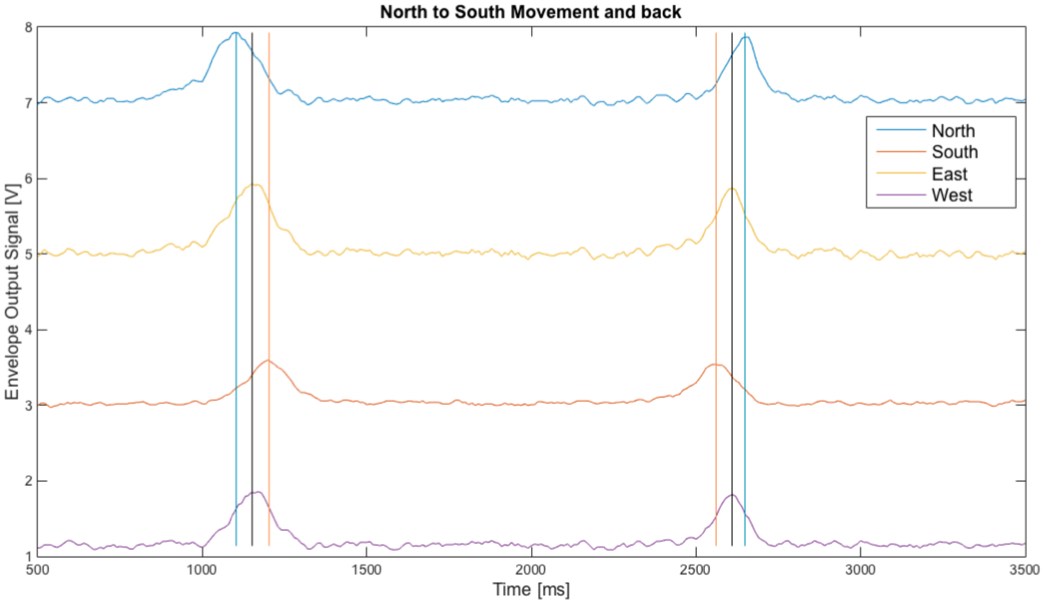

Figure 50. Photodiode signals in a situation analogous to the previous figure with the direction being North-South

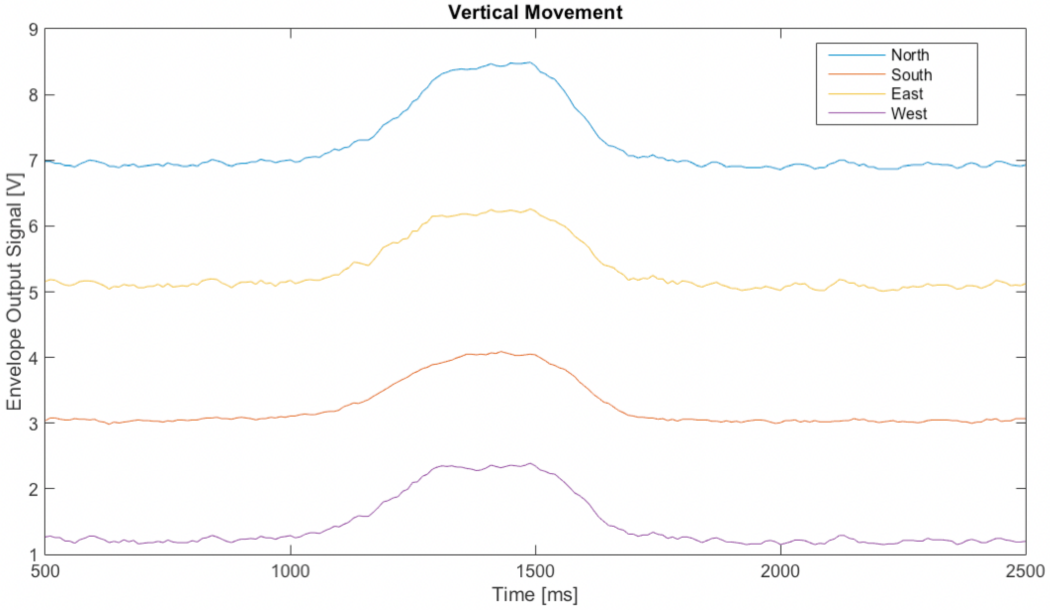

Figure 51. Photodiode response signal when the movement is vertically towards the tile.

It can be observed that the responses of all the photodiodes are synchronised.

The gesture sensing system was envisaged to offer a contact-less interaction with the tile. The proposed design and its following implementation are satisfying the requirements as illustrated in the figures above. During the demonstrators phase the system has shown no failures when users, unconscious of the functioning, were interacting with the tiles.

The proposed solution is furthermore showing a flexibility such to be used in other applications were proximity detection or gesture recognition is required and a contactless sensing system is needed.

5 Conclusion

LUMENTILE™ project had the primary goal of developing the technology framework for the production of a new, smart device, in three different models, as presented in the first chapter. Besides this, a relevant effort has been devoted to the preliminary industrialization steps of the technology, with the goal of approaching large-scale industrial production.

This dissertation has presented the work done by the candidate in the photonics and optoelectronics domains. The challenges in these aspects were related to integrating optoelectronic and optical devices inside a structure as the one prescribed by LUMENTILE™, being primarily a structural element than a high-tech device.

The main focus was in optimising the wall plug efficiency of the product, without sacrificing optical performances. A second aspect was related to the costs reduction, addressing the optical design and optoelectronic circuit architecture towards the use of non-standard materials, reduction of the number of components and production process simplification.

From a technical point of view, the topics addressed by the work were related to illumination and sensing systems. The candidate has presented results on the following:

- Light source identification and design of a driving system
- Design and development of an optical structure to offer uniform illumination of the tile surface
- Design and implementation of an optical gesture recognition sensing system.

The light source installed in LUMENTILE™ resulted to be standard high power semiconductor LED. Three of them, red, green and blue, are used in every individual light source to offer a large gamut of colour to the tile. A dedicated driving system was developed and presented.

The illumination created by the discrete LEDs were to be spread over the area of the tile in a uniform way. To obtain a good uniformity of the illumination on the tile surface, a light guide approach was proposed. This technology is known in the display field, where the requirements are though different from the ones of LUMENTILE™. The designed light guide is reconciling the mechanical properties required to this component and the visual appearance of the tile. The light guide needed to be a structural element embedded in the tile, requiring a low complexity in the assembly phase while keeping at minimum the number of components and costs. Together with this, the optical performances were not to be traded.

The gesture sensing system is exploiting the concept of triangulation to detect the movement of an object in front of the tile (a hand) and allows the interaction with the device. The system is based on an infrared emitter which illuminates the space in front of the tile, where the hand will wave to require any action to the tile. A portion of the light scattered by the hand is then sent back to the tile and detected by four photodiodes placed inside the tile for the detection. The detection system is operating with a homodyne scheme, isolating exclusively the frequency of operation, deleting or reducing all the incoherent signals.

The results obtained in the optoelectronic field, described in this dissertation, resulted appropriate and sufficient given the requirements set by the project. The systems designed and presented here were adopted and installed in all the prototypes developed by project so far and some of the solutions are now subject to a patent filing process which is likely to create a stable technological foreground for LUMENTILE™.

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