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FLAT LIGHT GUIDE - A SUSTAINABLE AND CREATIVE LIGHT SOURCE[1]

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Abstract

Light has always been used as a means of communication. As early as in the 4th century B.C. a hydraulic telegraph that was used in combination with fires has been developed by the Greeks. In 1821 Carl Friedrich Gauss invented heliotrope -an instrument that uses a mirror to reflect sunlight over great distances. Nowadays, light impulses travel on the principle of total reflection between materials of different density, inside round cross-section acrylic fibers -*light guides*- and are protected from inclement weather conditions and other disturbances from the surroundings. The result of such light *transportation* can be indirect -a transmission of data, or direct- a transmission of light with the purpose of illumination. Light that exits at the end of an optic fiber is usually formed as a point, as a line or, in our case, as a luminous surface. Light can also be intercepted on its way through a flat light guide, through a special surface treatment. Textures on the surface of sheets of acrylic glass form panels of either uniform or various brightness. Such panels can assume the role of the elements of an architectural luminous ambience. Transmission and reflectivity is also investigated, theoretical and practical, using light measurements on a physical model in order to show that luminous panels can also be used as floors/ceilings in multi-storey buildings in order to improve natural illumination and thus to reduce the cost of electrical lighting. Findings in the paper can bring useful information for architects, lighting designers and structural engineers.

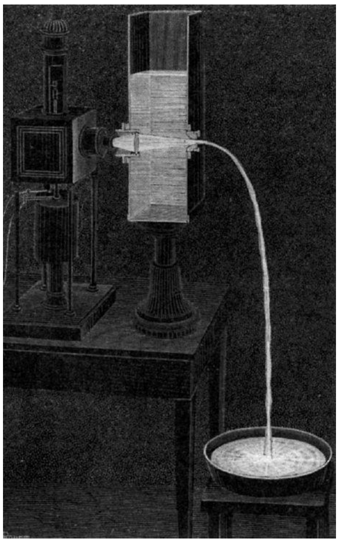
1. Introduction

Luminary design and production is as old as the history of artificial lighting. Luminaries as special objects reflected the state of the art in the technological progress of human societies. Early lamps were just poor and unreliable substitutions for natural light. Animal fat, vegetable wicks and stone or shell bodies were basic components of early lamps. Gradually new

[1] This topic has been originally published in a book of abstracts within the international simposium Balkan Light in Belgrade, Serbia in 2012. It has been revised and expanded, calculations and measurements of the light flux have been added since then.

materials, fuels and methods of production provided more sophisticated and more powerful lamps. The quality of artificial light also increased. Despite this fact these were still point light sources e.g., the flame of a candle or even the filament of the incandescent light bulb. When there was a need for stronger light these point light sources were multiplied as chandeliers or as clusters of floodlights. The discovery of Neon in 1898 and the fluorescent light tube in 1937 introduced linear illumination. Due to the need for more uniformly illuminated spaces (offices and production areas) flat luminaries were developed. These were, and are still, composed from linear fluorescent light tubes in combination with parabolic mirrors and diffusers that produce softer and more uniform light output. Such luminaires can be assembled to form fields of more or less homogenous brightness. Light is a physical phenomenon; the practical dynamics are known, and as such we know its journey through space -the distance from light-source to destination- is invisible to the eye until it strikes an obstacle and bounces from its surface. Only then does the wave become perceptible. Now light can be transported long distances.

Figure 1. **Daniel Colladon Light fountain (1841)**



Source: Hecht (2014: 14).

In 1841 the Swiss physicist Jean Daniel Colladon demonstrated the transfer of light in a jet of water (Hecht, 2004: 13). In 1842 the French physicist and mathematician Jacques Babinet reported on how light can be guided through a curved glass tube as through a jet of water (Figure 1) (Hecht, 2004: 15). In 1880 the American researcher William Wheeler patented a light tube that uses the principle of total reflection for transportation of light. Today optic fibers use similar principles of refraction of light between two different densities of materials for the transportation of data. Light *waves* bounce, at minute angles, from the inner surface of the light guide and can theoretically travel infinitely. A light moving through a light guide can also be intercepted where needed. A small cut into the surface or impurity in the material of a light guide is sufficient for light to exit the light guide. Light guides can be solid and round shaped - producing a point light source at the end; or solid and flat shaped, producing a linear light source at the end. A flat light source at the end of a light guide is a logical continuation of the previous two principles. Light Emitting Diode (LED) is one of the most promising light sources. High light output and low consumption of electric energy as well as small dimensions make the

LED a desirable light source in the field of architectural lighting. However, when considering LED point or linear light sources glare, due to high levels of brightness upon very small surfaces, can become an important issue; for this reason LED's, when considering architectural situations, need to be covered with translucent materials that make their light less sharp and distributes brightness over broader surfaces. The downside of this is that at the same time it lowers the LED’s efficiency and adds to the overall dimension of a LED luminaire.

2. A plane - the most important element of the architectonic space

In the composition of a visual construction, a plane serves to define the limits or boundaries of a volume. If architecture as visual art deals specifically with the formation of three-dimensional volumes of mass and space, then the plane should be regarded as a key element in the vocabulary of architectural design (Ching, 2007: 18).

Surfaces are becoming increasingly transient. As we advance further into the future, smart materials will continue to advance and alter the way building materials function. Now, we have glass that can change transparencies and sensors that can actuate LED surface lighting (Lehman, 2009).

3. Basic terms of the illumination of the architectonic space

Light: It is the basic quantity, the construction material that can be shaped; light itself is invisible.
Measure: Light can be measured as an electromagnetic undulation or as a flux of particles – photons.

Lighting: a procedure, a tool that is used to produce and shape light. Lighting depends on three basic elements:

- Light source/luminaire (a lamp or the Sun): the most important primary component. Power, light flux, color temperature, color, flicker (with discharge lamps) are basic quantities of light. A luminaire can emit light in one or more directions or omni-directionally.

- Obstacles in the path of the light are the second most important tool for shaping light. These are surfaces that intercept light and reflect it in various directions thus defining a luminous ambience. Light ambience depends on the properties of the surface: smoothness, color, dimension and shape.

- Shadow and shade are natural consequences. Shadows contribute to the spatial design and affect the impression of an architectonic space. Shadows also help regarding 3-dimensional perception and orientation.

Illumination is the final result of lighting upon a surface. Illumination is a photometric quantity, invisible to the eye, but can be measured using a lux meter.

Brightness is a quantity of light reflected from a surface under a specific angle that is perceived by the human eye.

4. Basic types of luminaires regarding the emission of light

A Point-Light luminaire is a light source where, theoretically, one bright point (or small surface) emits light. Its housing and optics are so designed that the illuminated area on a surface has a shape of cone or the light spreads omni-directionally. No dimension of the luminaire is emphasized. Incandescent lamps, simple halogen and metal halogen lamps, high-pressure sodium lamps, compact fluorescent lamps and LEDs are typical point-light sources.

A Linear luminaire is a light source that has one dimension strongly emphasized. Its housing and optics are so designed that the illuminated area on a surface has a shape of narrow or wide strips. Fluorescent tubes, neon-filled tubes, electroluminescent tapes, LED tapes w/ diffusers are examples.

A Flat luminaire is a light source that has two dimensions strongly emphasized. Its housing is very thin and it emits light as an evenly bright surface. Examples are Flat Electroluminescent Screens and OLED.

It should be emphasized that the *spatial perception* of the above three types of luminaires can change regarding to the distance from which they are observed. A flat light source that is perceived at a distance of 50 cm can be perceived as a point at a distance of 50 m. Similarly, an array of point LEDs at a distance of 50 cm can be perceived as a bright surface at a distance of 50 m.

5. Light guides

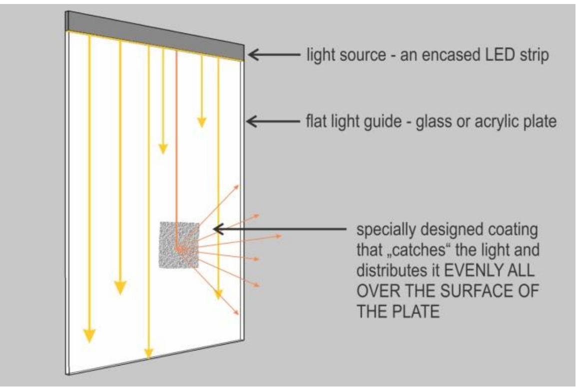
As noted above, light can be, using the principle of total reflection from a light guide inner surface (light tube or optic cable), transported between different parts of a house or different areas of a city. Light enters a light guide on one end and exits on the other. The exit of light from a light guide can be direct and simple or it can be enhanced using special optic lenses or optic filters; this depends on the demands of a particular architectural design. Large light tubes can transport sunlight into underground space, the smallest can help with endoscopic examinations or illuminate interesting details on fashion creations

6. Flat light guide - luminous plate as a multi-purpose luminary for architectural lighting

6.1 The principle of operation

The luminous plate is, from an architectural point of view, a rectangular plate that when charged emits a double-sided uniform light flux across its entire surface. The brightness of the entire surface is also distributed evenly. The light source, an LED strip, is placed on one of the four edges of the plate. The plate itself can be made of glass or similar transparent material, 5 mm. thick (Figure 2).

Figure 2. **Luminous plate - the principle of operation**



Source: Novljan (2012).

It works on the principle of a light guide -total reflection of light on the border between two differently dense materials- glass and air. The light *travels* through the glass from the light source towards the opposite edge. If the light flux is disturbed on its path through the glass- with a scratch or similar defect- light will exit the glass on this particular spot because the scratch acts as a micro mirror. In our case the surface of the plate is treated with a special coating, made of a specially designed array of small *dots*; these dots intercept the light passing through the glass and redirect it out of the plate. The result is an evenly bright surface composed of an array of shiny dots that can form an uniformly bright surface with very even distribution of light or various graphic patterns, textures, signs and other motives. Even one hi-power LED, placed in one of the corners of the luminous plate (with properly calculated and positioned *dots* is sufficient to make the system work i.e. to evenly illuminate the whole surface.

7. Possible architectural applications of the luminous plate

7.1 As an integral part of a piece of furniture

Figure 3. **A light shelf provides local and general illumination**

Source: Rihtar (2011).

Furniture is an important component in every interior design. Walls, floors and ceilings constitute an *envelope* of space and furniture can fill the space. The wardrobe is a typical piece of furniture that is used in almost every apartment. The arrangement of the shelves, drawers and partition walls in a wardrobe sometimes makes searching for a specific piece of clothes difficult, particularly in a poorly illuminated room. Small lamps, put inside the wardrobe somehow address the problem but the light produced by such lamps can be quite sharp producing acute shadows. The luminous plate can substitute any shelf (Figure 3) or partition wall of a wardrobe, creating a softer, more generally uniform illuminated interior of the wardrobe. Shelving in other rooms (offices, bars, reception desks) can be designed in this way. Many pieces of furniture can become hybridized and multifunctional using luminous plates.

7.2 Illumination of a staircase

Figure 4. **Luminous plates as glass railing**

Source: Novljan (2012).

The proper illumination of staircases has always been of great importance. Andrea Palladio in his *Four Books on Architecture* writes: "A staircase must have three openings - for the entrance, for the exit and for the illumination.”. The optimal illumination of stairs is side illumination. In this way sharp shadows on the treads are avoided so users have a more secure feeling. This is most important when elderly users have to be taken into account. Luminous plates can be integrated into a staircase as part of the railing system (Figure 4) or as hybrid elements, serving dual purposes: ambient illumination and prevention of falling. Movement sensors can be used to switch lights on and off considering the movement of a person on the staircase or to add a dynamic component to an interior as well as to create a feeling of personal security. Various colours and textures can also be applied to the walls of the staircase to improve the visual appearance of an, usually uninteresting space, especially in the case of multi-residential buildings. In this way the staircase becomes a central place in a building that connects all floors not just in functional but also in symbolical manner.

7.3 Illuminated partition wall

Figure 5. **A digital simulation of an arrangement of cubicles used for a press center**

Source: Novljan (2012).

Partition walls serve both as physical and visual spatial separation; they can be made of various materials such as wood, metal, plaster etc. In cases when transparency of the partition is needed glass or other transparent materials can be used. Regarding partition structures, luminous plates can assume the dual role of separator and illuminator. When used in large office rooms such plates can create illuminated working cubicles: light on -a cubicle is occupied, light off- a cubicle is not occupied. If the light is turned on, one can not see through the wall (Figure 5). The luminous plate thus becomes an integrated architectural sign that can create multiple variations in spatial composition, also as an office arrangement. As a modular element it can be used for creation of opened ambiences like places for news reporters or for creation of closed micro-ambiences like meeting rooms within larger spaces.

7.4 Interior decorative Surface

In places like hotels and bank lobbies various decorative surfaces -tapestries or paintings etc.- can be observed. Such qualitative surfaces, full of colors, textures and expressive materials add to the importance and exclusiveness of such places. The decorative surfaces can be additionally illuminated, using emphasized light. Luminaires for this purpose (spot lights, linear lights) are usually placed at a distance, sometimes causing undesired shadows or very close, creating a grazing effect that emphasizes imperfections on the illuminated surface. Luminous plates as a decorative spatial elements -walls, floors, ceiling panels or a reception desks- do not need additional lighting because they produce their own light that can be used as task, ambient or decorative lighting. Besides its decorative effect it also has a role of attraction and orientation e.g., emphasizing areas in front of elevators.

7.5 Extended roof at the entrance into a house

The illuminated entrance of a house should obey several rules: it should not cause sharp shadows on the face of a person who is standing in front of the entrance; it should not produce glare for the person that is standing in front of the entrance; it should illuminate the immediate surroundings of the entrance (floor, walls and ceiling, if any).

An entrance should also provide minimal protection against atmospheric precipitations. Luminous plates that are an integral part of an extended roof can adhere to all of the aforementioned rules. It produces soft, diffuse light, protects visitors against atmospheric precipitations and illuminates a portion of the façade around the entrance.

7.6 A façade panel

Façades of contemporary office buildings are often designed as glass surfaces -as door and window glazing or, simply, as a glass curtain that reflects the perimeter of a building and so dematerializing the mass of the building. At night, instead of placing window curtains, luminous plates that are integrated as a part of glazing and used as a *light curtains* illuminating interiors (offices), blocks views from the exterior and illuminates parts of the exterior of the building.

7.7 A decorative luminary

Although luminous plates in the before mentioned cases can substitute *usual* luminaires, it can also assume a normative role. The properties of a luminous plate, from dimension, shape, color of light, various kinds of glass surface treatment (pattern-like or motif), and possible additions...reflective plates, lenses and lampshades all offer a wide range of possibilities for design.

7.8 Luminous floor/ceiling surfaces

A special attention in this paper space belongs to a floor and a ceiling, despite the fact that these surfaces are, visually speaking, not among the most important spatial elements as are the wall surfaces. F. Ching (2007) distinguishes floor and ceiling surfaces by their primary function as:

- the overhead plane can be either the roof that shelters the interior spaces of a building from the climatic elements, or the ceiling plane that forms the upper enclosing surface of a room.

- the base plane can either be the ground plane that serves as the physical and visual base for building forms, or the floor plane that forms the lower enclosing surface of a room upon which we walk (Ching, 2007: 19).

So, how can we understand floor and ceiling surfaces in the terms of natural and electrical illumination? Although very high levels of daylight illumination (…Lux bright sky, … Lux overcast sky and the glass façade in the depth of an *usual* building is not very bright. Therefore building regulations in Slovenia limit the depth of the room that must not be greater than the height of the room, multiplied by 3.
Natural light/sunlight enters the room and therefore the floor where it is partially reflected, partially absorbed. The reflectance factors of different materials are defined by standards. Most of the light that falls on a floor is absorbed; reflected light is diffused because mirror/specular reflection of the light on the floor should not be tolerated due to the possibility of glare that is generally undesirable. This diffusion additionally increases the level of illumination in the window area where the level is already high. On the other hand the absorption of the light increases the temperature of the floor in the window area and therefore the need for cooling of the room. Direct light that falls on the floor can be treated as useless and even disturbing. So, the floor can be recognized as one reason for insufficient illumination of the room.

The most effective way of illumination of an interior is by using zenithal light that is light which enters a room from above. This can be achieved by using skylights that are positioned in a roof. If natural light that enters through such skylights in a multi-storey building is *extended* though lower storeys, using transparent or translucent floor/ceiling surfaces, the effect of zenithal light can be achieved throughout the whole height of a building.

A - Transparent or translucent floors/ceilings

Transition of the natural light into the depth of a building enables more efficient use of all areas of the *floor plan*, not just those that are close to façade surface but also those positioned in the core of a floor plan.

Transition of the visible and thermal part of the electromagnetic waves enables more balanced heating of the building as a whole.

More useful surfaces in the depth of the *floor plan* and consequently reduced façade surfaces means less thermal loss during winter months and less need for cooling during summer months. The role of transmitting natural light from skylights to lower storeys is changed in the night time. Luminous plates become elements of the floor/ceiling and serves as an emitter and a transmitter of the light in vertical direction. These luminous surfaces can be recognized as hybrid architectural and structural elements because they serve as floor and as the luminary in the same time. Each luminous plate starting from top floor downwards adds a certain amount to the overall illumination.

B - Calculation

A calculation has been done with the aim to confirm and support above statements mathematically.

Consider the case of a single layer of dielectric between two infinite media.

Light beam incident normally on a planar interface of the layer.

Fraction of the light is reflected from the front surface, while the rest enters the medium and propagates through it. If any of this light reaches the back surface, it can be reflected again, or it can be transmitted through to the other side.

The optical phenomena described can be quantified by a number of parameters that determine the properties of the medium at the macroscopic level. The simplest group of parameters used for energy flow analysis is reflection, propagation and transmission.

The reflection on the layer is described by the reflectivity *R* and is defined as the ratio of the reflected power to the power incident on the layer. The transmissivity *T* is defined as the ratio of the transmitted power to the incident power. If there is no absorption or scattering, then by conservation of energy we must have that:

$$R+T=1$$

In transparent material such as glass in the visible region of the spectrum the absorption coefficient and the scattering are very small.

Now suppose that we have **N** identical equally spaced layers of dielectric numbered **i = 1, 2, 3, . . . N**.

The multilayer optical structure form a Stack of chambers.

The gap between layers **i** and **i+1** is denoted by **i -** th chamber. Gap distance is large compared with the *coherence length of the light.* Let's set that layers are horizontally placed and the incoming light is from above.

On each layer **i** the light is partially reflected and partially transmitted according to reflectivity of the layer.

The upward reflected part of incoming light flux from arbitrary **i**-th layer will be partially reflected again downward from all of the upper **i-1** layers.

Total light flux directed downwards is so the sum of transmitted initial flux and all partially reflected fluxes from upper layers.

By calculating the sum of infinite series we determine the expression for downward directed light flux in **i**-th chamber

$$I_i^{down} = \frac{1-R+(N-i)R}{1+(N-1)R}$$

and upward directed light flux

$$I_i^{up} = \frac{(N-i)R}{1+(N-1)R}.$$

The curve for light flux I_i^{down} calculated at actual values of R and N is much higher than curve for just transmitted initial light flux (see Figure 1).

Total reflectivity of the multilayer structure is

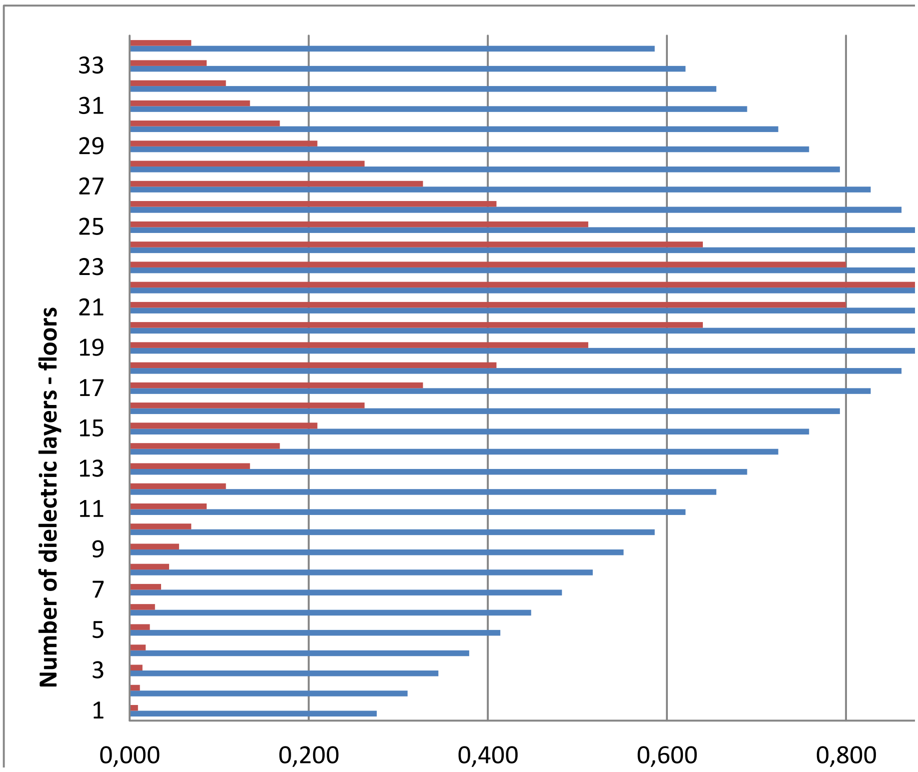
$$1 - \frac{1-R}{1+(N-1)R}$$

and increases with growing N.

At large N, the chambers in the middle of the structure have above and below the mirror like surface.

So the light from the light source in that chamber will be reflected up and down for many times. A set of two mirrors arranged to cause light to propagate in a closed path is called an optical resonator. This *container* for light is able to store photons for a certain time within its volume.

Figure 6. **Curves of light flux from 22th chamber in case of calculation consider the reflectivity of dielectric layer (blue line) and transmitted initial light flux (red line)**



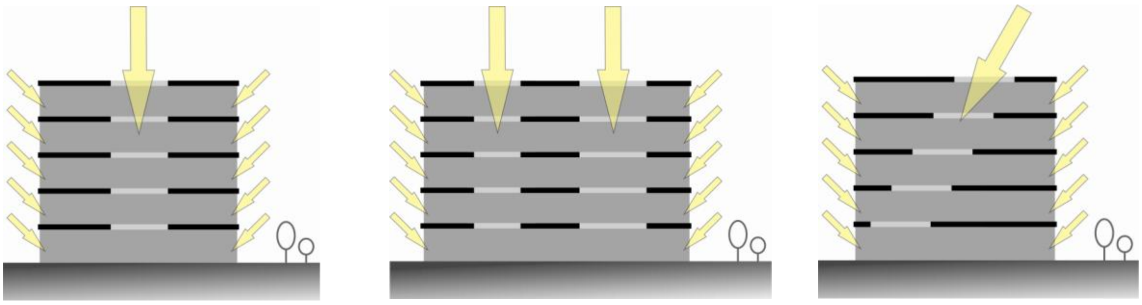
Source: Rihtar (2011).

The calculation is made for normal incidence of light but is valid for oblique incidence of energy flux. The theoretical results are verified with measured light intensity on optical model. Stacks of chambers with different number N of dielectric layers (PMMA) is exposed to narrow light beam or diffuse light beam. Very good agreement between measurements and calculation is observed.

8. Conclusion

When this physical model is converted into architectural environment then stack of chambers can be presented with multi-storey building and dielectric layers with walkable glass floor. A number of different kind of use of luminous floors/ceilings in multi storey buildings can be developed (Figure 7). The positions of the glass floor/ceiling within a multi storey building can vary ragarding a floorplan and/or cross section, depending on the function of a building, architectural design, number of storeys, orientation and geographical situation of a building.

Figure 7. **Various possible positions of the luminous transparent floor/ceiling within the building. Yellow arrows indicate the penetration of the direct sun light into the building**



Source: Novljan (2013).

A Luminous ambience is a special spatial layer that is defined by various light sources and surfaces from which light reflects. The luminous ambience is an important element of architectural space. It enables different impressions of the same material space: dull, contrast, balanced, dynamic, flat… Luminaires of all kinds have been treated as special and important elements of the human living environment since the *discovery* of fire. Luminaires became an important and independent piece of interior and urban ambiences. Merging architectural elements gave birth to new types of luminaires which are not merely self-standing compositional pieces, but an integral part of other architectural elements as well. Flat light guides -luminous plates that use two-dimensional emission of light- can substitute or upgrade ubiquitous pieces of furniture or architectural elements of the interior and exterior environment. Special surface treatments and coatings foster the creation of homogenously bright surfaces. Luminous plates can emit light as one-sided or double-sided, in white or in color. They can be particularly useful where diffuse light is appreciated. Their thin flat shape and low energy consumption is of prime advantage and is an argument, in certain situations, against fluorescent and other types of lamps. Luminous plates can be produced in non-standard dimensions and are very adaptable to specific architectural designs. They can substitute or upgrade existing interior and exterior architectural elements.

Flat light guides stand between the fluorescent and OLED technology. They are more robust than OLED, they can be manufactured in larger dimensions than OLED -up to 120x240cm, they are weatherproof, they have low operating and maintenance cost and long operational life. Also these panels (can be implemented as transparent floors/ceilings using both natural and electrical illumination. In multi-storey buildings, in both cases -using natural or electrical lightinter reflections between individual glass floor and ceiling surfaces increase the quantity of light and improve the quality of light by creating luminous *wells* in the depth of a floor plan or in the depth of a cross section, converting them from darkest to brightest areas of a building. The path of the Sun can also be calculated and these luminous *wells* can be positioned and designed according to this, allowing the sun light to be used optimally during the day and during the year. It can be believed that, in near future, a new architectural language or key will emerge. It will be both global (international) and local (regional) where location and local climate conditions supported by high technology will again become most important factor to consider within an architectural design process.

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