Light Guides
Application Note

Introduction
Light Guides are used wherever the light of a lightsource should be distributed homogeneously over a particular area, when there is a spatial distance between light source and the area which is to be illuminated.

Definition of application fields
Following some application examples utilizing light guides are listed.

- LCD Backlighting, e.g.
    - Car radio
    - Cellular phone
    - Multimeter

- Marking
    - Dash boards
    - Status indication of electronic systems
    - Road-marking
    - Step-marking:
        - On the wall
        - On the steps
    - Seat-marking: (e.g. Theater, cinema, ...)
        - Colored or white
        - With numbers or letters
    - Ambience-lighting inside furniture
        - Cupboard
        - Shelf
    - Design-light-effects:
        - At furniture`s
            - Table
            - Bed
        - Ambience-light
    - Advertisement lighting (e.g. backlighted letters, profiles)
    - Emergency exit light

This application brief is confined with the LED as light source for light guides. A light guide module is a combination of the light guide itself and LED‘s mounted to a circuit substrate. Light guides are used in a wide range of application fields. Due to the wide variety of light guide designs and applications, use of light guides with LED‘s as lighting element is an ideal combination. Use of conventional lamps such as incandescent lamp or flourescent tubes with light guides is also possible. Due to the wide radiation angle and the large package of conventional lamps, LED‘s are much more suitable for light guide systems. Detailed information about advantages of LEDs are given in the chapter „Reasons for the need of LED instead of incandescent lamps and flourescent tube“.

Basics
To have a better understanding of how light is guided into a light guide system some, fundamental theories are considered first.
A light guide is a non absorbing material, constructed to transport light. A light guide uses the mechanism of reflection caused by two materials with a different refractive index. It transports light from one location to another, by using total reflection of light at the boundary to the surrounding medium.

Consider a light ray which crosses through an interface at an incident angle (Figure 1). The interface is the boundary between two light transparent mediums. The mediums have the refractive index values designated n_1 and n_2, provided $n_2>n_1$. Further the incidence angle is defined as ε_1, refraction angle is defined as ε_2.

Snell`s law is defined:

$$n_1 * \sin\varepsilon_1 = n_2 * \sin\varepsilon_2 \qquad (1)$$

Implication from snell`s law is that at the transition from an optical skinner medium to a heavier medium is, the light ray is refracted to the plump. In the reserved case (Heavier -> skinner) the light ray is refracted from the plump.

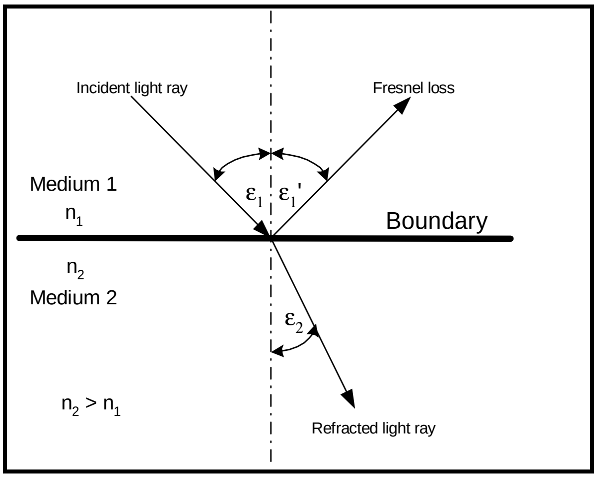


Figure 1

Total internal reflection:
When the refracted angle of a light ray reaches 90° out of the light guide, the angle is defined as the critical angle ε_g (Figure 2, ε_2). For an incident angle $\varepsilon > \varepsilon_g$ the forayed light ray is totally reflected on the boundary.

Maximum allowable angle ε_g (critical angle) for the light ray is reached when the refraction angle is 90°.

$$\sin\varepsilon_g = n_1/n_2 * \sin 90° \qquad (2)$$

$$\varepsilon = \arcsin n_1/n_2 \qquad (n_2>n_1) \qquad (3)$$

The anterior contemplation`s are essential for in-coupling transport and out-coupling of light in light guide systems.

Fresnel loss:
At the transition of a boundary, losses are caused by reflection. These losses are termed as fresnel loss.

Fresnel loss = $100 * [(n_1-n_2)/(n_1+n_2)]^2$ %
(4)

Loss at the boundary air to plastic (refraction index ~ 1,5) is approx. 4%.

The preceded theoretical considerations are fundamental for light guide design. Light guide design can be split into the following parts:

- Light coupling into the light guide
- Light transport inside the light guide
- Light coupling out of the light guide

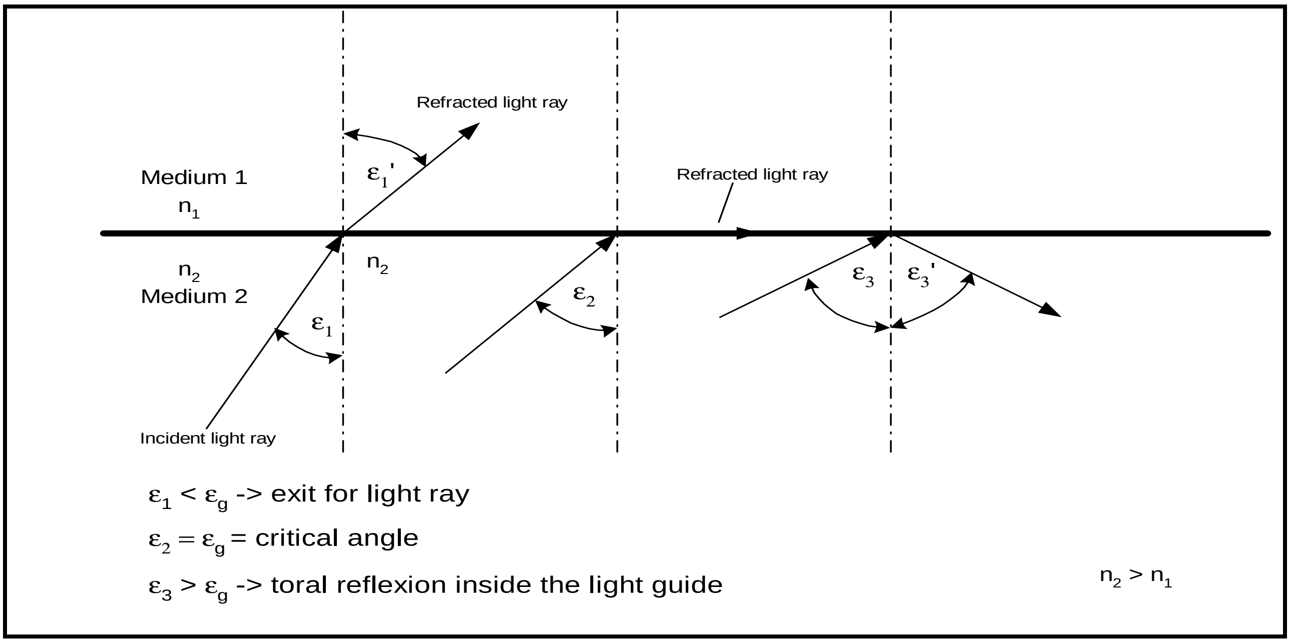


Figure 2

Light guide design

Luminous flux coupling of LED Light into a light guide

For maximum performance using a LED light source, it is important to build a system with high coupling efficiency. For a light guide module and a light guide mounted to a PCB, using SIDELED from OSRAM Opto Semiconductors is a very good solution. Table 1 points out different possibilities for LED light coupling into a light guide. Advantages and disadvantages are listed. The following describes the basics for light guide design. A smooth surface of a light guide is important at the in-coupling side to achieve a good uniform coupling and to avoid reflections (Figure 3).

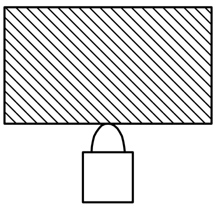
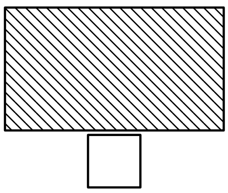
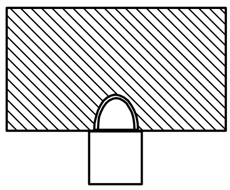
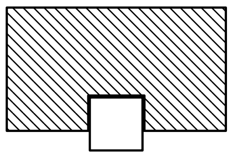
Set on Light Guide		"Inside" Light Guide	
Lens	Flat	Lens	Flat
			
- Transition from LED to light guide (interface)	- Transition from LED to light guide (interface) without index-matching	+ good interface LED to light guide	+ good interface LED to light guide
- Large distance caused by lens	+ slight distance (space saving)	- Hole in light guide (tooling costs)	- hole in light guide (tooling costs)
- narrow incidence angle - long hot spot	+ slight hot spot length, better with index-matching (but cost intensive)	- long hot spot	+ slight hot spot length, better with index-matching + wide incident angle
		- mounting depth	- mounting depth

Table 1

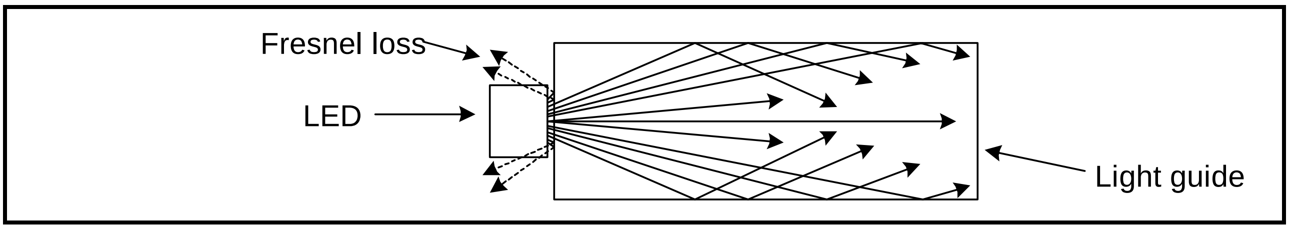


Figure 3

Another improvement of light coupling is achieved with refraction index matching (Figure 4). This prevents losses caused by fresnel reflection and improves the out-coupling efficiency of the LED. Without index matching, refraction index changes in following the form ~ 1.5 (plastic) – 1.0 (air) - ~1.5 (plastic). In many applications index matching causes higher manufacturing costs for the system. For this reason, it is necessary to make a performance and cost analysis of the system, to achieve the best setup.

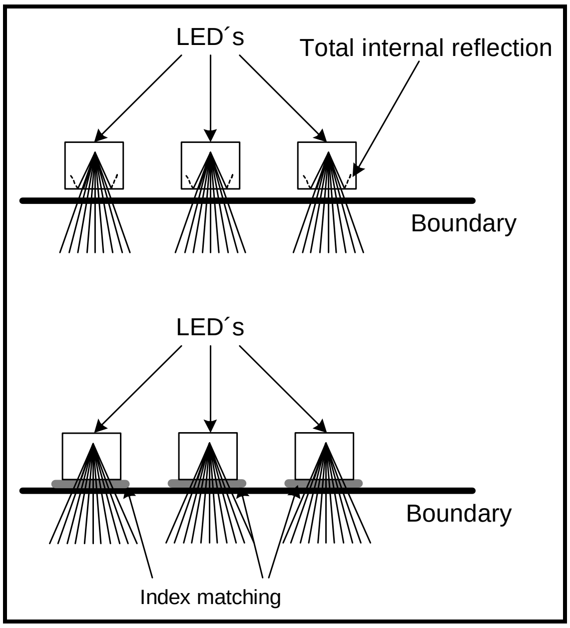


Figure 4

Property of light guiding
To lead light inside a light guide, it is important to have a high reflectance at the boundary. A good reflectance is reached with a smooth surface (total internally reflection). Improvement in reflection can be achieved by adding a silver foil or white painted surface. Another possible reflector is a reflective box surrounding the light guide on the non LED edges. Diagonal ray`s less than the critical angle are reflected which would otherwise escape without a reflection coating.

For light out-coupling of the light guide a defined roughness on the out-coupling surface is necessary. This so called „dot structure" is made during the molding or as an additional process of printing.

Light out-coupling of a light guide
A diffused surface is necessary to present random angles to internal light rays. This causes the light ray`s to escape from the light guide.
An application example of a light guide is described (Figure 5). Light being coupled into the light guide is from one side. The objective is to achieve a uniform out-coupling intensity over the whole out-coupling area. Caused by changing luminous flux (by light out-coupling) inside the light guide over its length, it is necessary to achieve an adapted change of out-coupling efficiency. For the luminous flux distribution inside the light guide, the following boundary conditions are assumed:

- continuos rough surface on one side
- no reflectors on the other surfaces

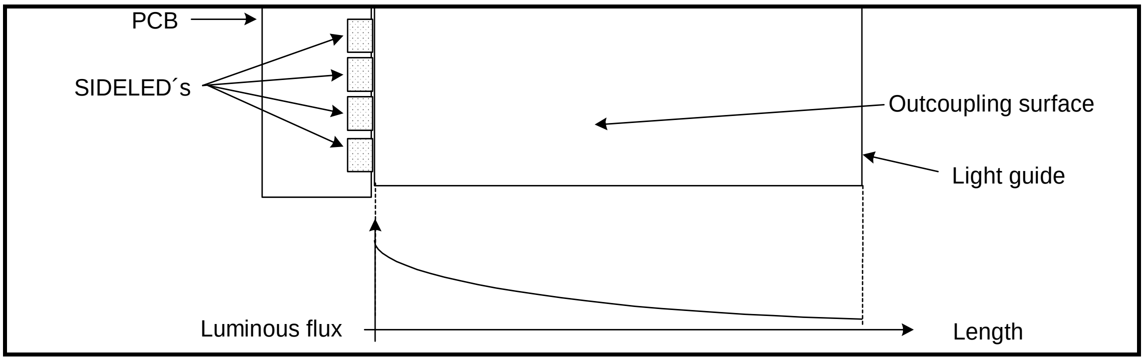


Figure 5

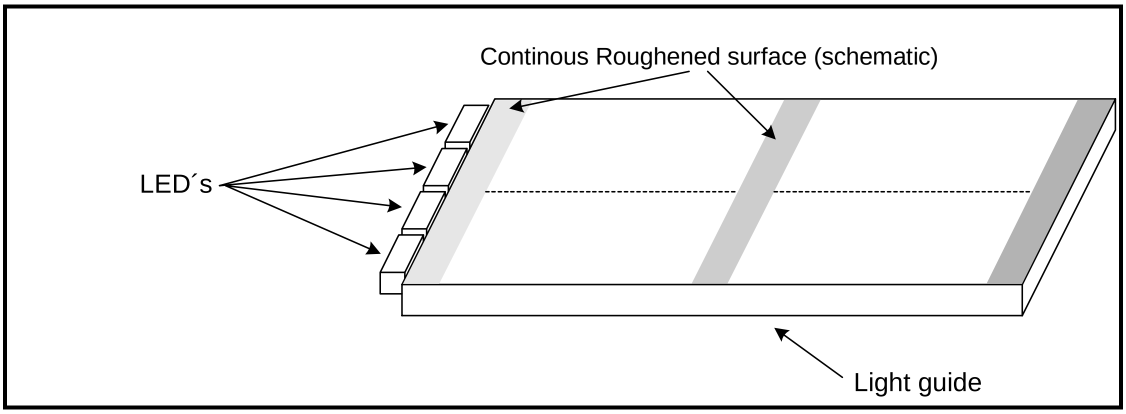


Figure 6

Following possible setup variations are described.

Rough surface
A roughened surface enables the possibility to build up very fast a light guide with a continous output intensity (Figure 6). Such an element is e.g. produced with sandpaper. Those method is just useable for sample production.

Rough dot surfaces on backside
Another possible setup is to bring up small rough surface dots on backside of the light guide (Figure 7). By varying the number and density of these dots, it is possible to vary the out-coupling coefficient. To avoid light spots, it is necessary to bring up the rough dots on the backside of the light guide. By reflecting light to the out-coupling side via a reflector through a diffuser, it is possible to achieve a very uniform radiation of the light guide. The rough dots are printed on the light guide surface.

Microdots
By including small hemispheres on the light guide, it is possible to setup defined out-coupling spots (Figure 8). By changing the number of dots per area unit over the length of the light guide, it is possible to achieve a uniform intensity. In most applications, it is important to use a diffusion foil on the microdots. The dots can be brought up on top or bottom side of the light guide. Such dots are usually produced during the molding process of the light guides.

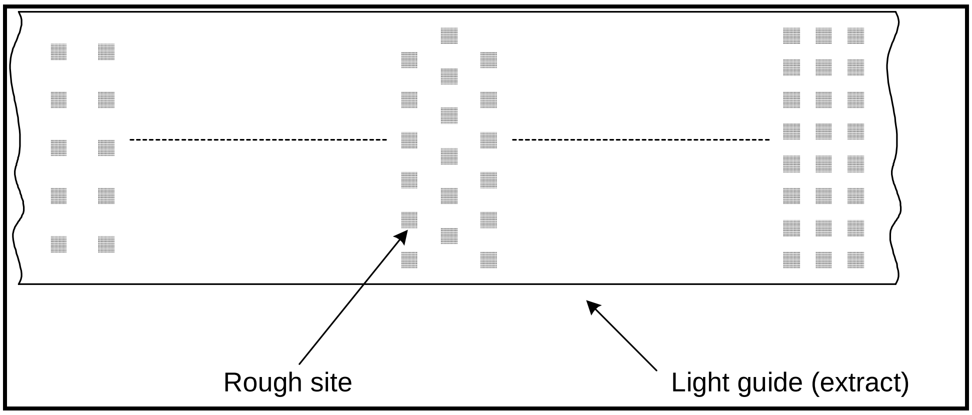


Figure 7

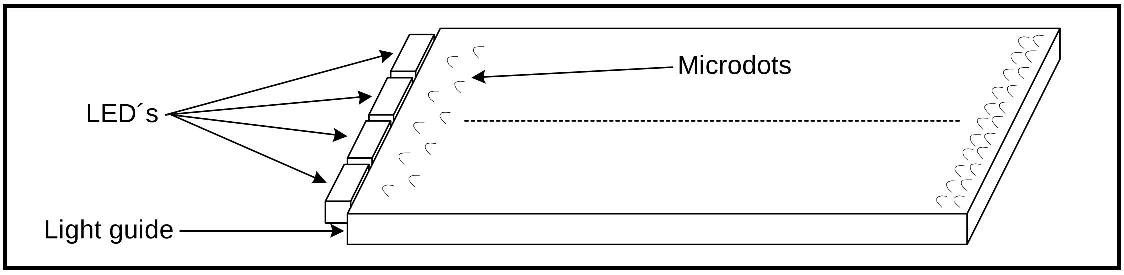


Figure 8

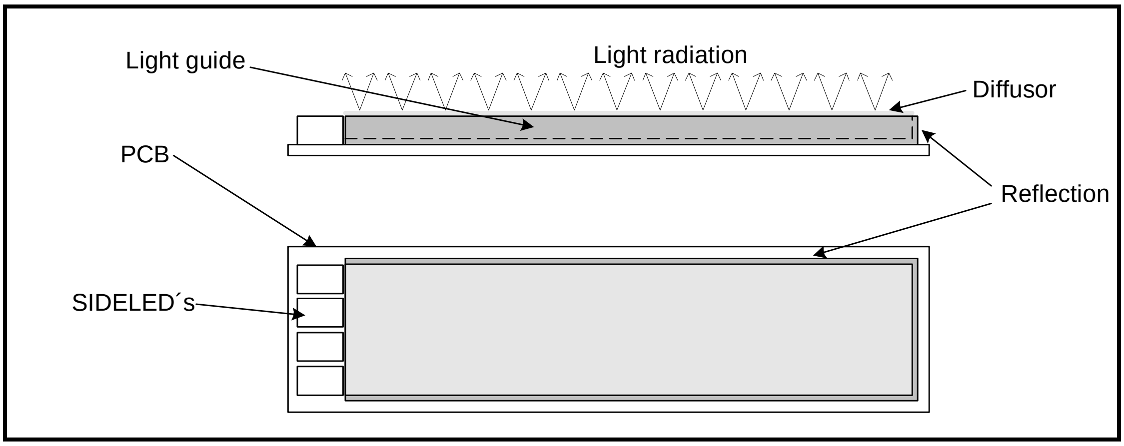


Figure 9

Reflector

If a light guide only radiates from one side, it is useful to setup all other sides as a reflector. Figure 9 shows a possible setup of a light guide with reflectors on all not radiating sides.

Diffuser

To achieve a uniform light radiation of a light guide, it is very useful to put a diffuser foil in front of the radiating side. With a diffuser foil a uniform and vectored radiation is achieved.

Hot Spots

At the incidence area, hot spots are caused by the radiation angle of the LED (Figure 10). Hot spot means that the LED spot causes non homogeneous regions at the in-coupling side. Dependent on radiation angle and light guide material, such hot spots have different expansion inside the light guide. The aim is to keep the hot spots in the outer rim of the light guide an to cover them in the application.

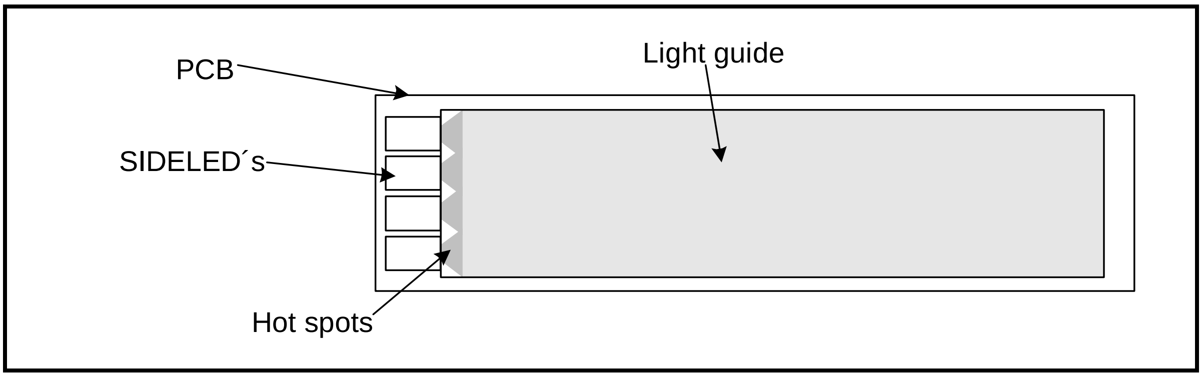


Figure 10

Setup Variations

Possible setup variants are sketched in the following figures.

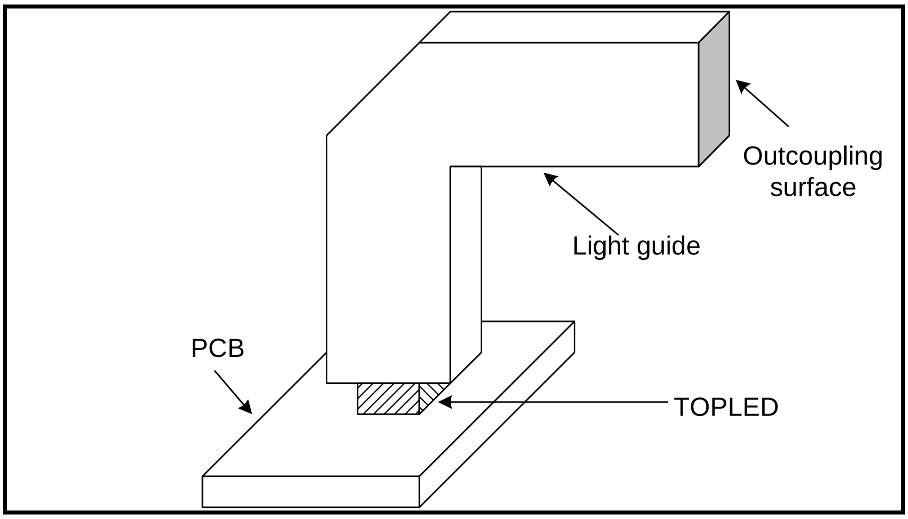


Figure 11

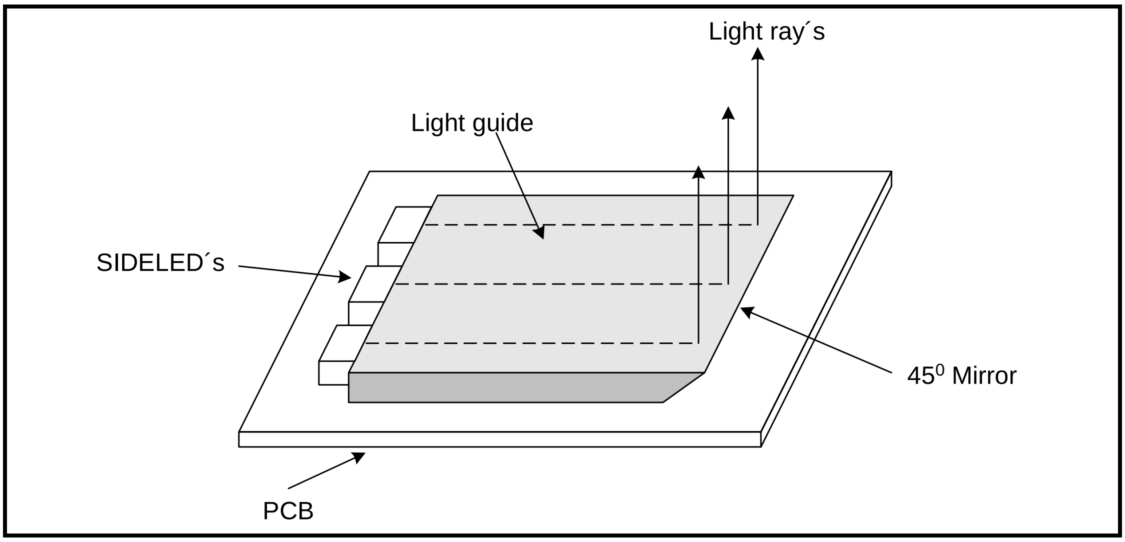


Figure 12

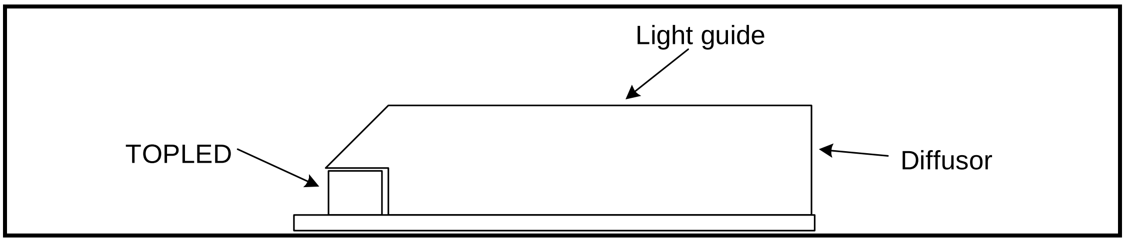


Figure 13

Reasons for the need of LED instead of incandescent lamp or flourescent tube

- Small package dimension
- Shock resistance
- Radiation angle
- Slight weight
- High reliability / longer life time
- Lower power consumption at colored applications
- Better light coupling properties in light guides because of special designed viewing angles
- Usage of SMD pick & place machines

Small package dimensions
One important factor in light guide design in lamp modules, is to provide the smallest package size possible for. Through a small package size, the design possibilities of the system increase dramatically. With conventional lamps it is necessary to build a large housing, that is dependent on the lamp dimensions. Design liberty of light guide systems is restricted by the lamp size.

Shock resistance
Compared to incandescent lamps, LEDs are very insensitive against mechanical shock. An LED is constructed without any moving components and is a very compact design that resists high mechanical shock over a long period.

The construction of an LED consists of a chip sitting in a reflector cup that is attached to a metal leadframe. The connection to the second leadframe is done with a wire bond. All of this is encapsulated with special optical grade epoxy. In Surface Mount Technology (SMT) the chip is sitting on a flat leadframe inside a package that is formed to a reflector. The epoxy is then casted in this package, shaping another encapsulated form. Unlike an incandescent lamp there is no delicate glass cover or fragile long thin wire filament to break. This is very important particulary for mobile phone and automotive applications.

Radiation angle
There are various LED packages that have different radiation angles offered from OSRAM Opto Semiconductors. It is possible to select LEDs with an optimal radiation angle for a specific application. Conventional lamps usually radiate 360°. Reflectors expand the size of the system which causes larger packages.

Less weight
One of the most important factors of an LED is its less weight. The weight of an usual TOPLED is only 35mg. This small weight is negligible to the weight of PCB, solder and light guide. Compared to incandescent lamps the weight of a LED is only several percent. Low package size together with its weight offers many opportunities in light guide designs.

High reliability
The average life time of incandescent lamps is in the range of 1000hours, of flourescent tubes 12.000hours.
The definition of MTBF is different for conventional lamps and LEDs.
MTBF for conventional lamps is the statistical average time till a catastropic failure for a given type of lamps. To achieve this value, a specific quantity of lamps are tested at specified conditions. The time, when one half of the lamps being tested have failed due to a catastrophic failure is taken as the **M**ean **T**ime **B**efore **F**ailure.
MTBF of LEDs is the calculated time between possible catastrophic failures of a given type of LED device. Catastrophic failure is described, that the LED does not occur during the lifetime testing, which is based on high operating temperature, when operated under certain conditions (usually 85°C and max.forward current).

LEDs, as with all light sources, have a gradual decrease in intensity over time. When LEDs emit 50% of their original light output, they are considered to have reached the end of their useful operating lifetime. For

OSRAM Opto Semiconductors high brightness LEDs estimated average light output degradation is less than 40% after 100.000 hours. This degradation time is valid for a temperature of 85%C and high current (e.g. POWER TOPLED in amber, I_{max} = 70mA). For continuos operation a lifetime over 10 years is estimated, causing no need of replacement of LED`s. For occasional operation, lifetime is increased due to the non operating time.

OSRAM Opto Semiconductors possess a high packaging know how in order to assure perfect and economical processing. OSRAM Opto Semiconductors LED`s in SMT and through hole packages are developed and qualified for worst case climate conditions. They meet the high automotive specifications with test conditions at 85°C and 85% relative humidity. In addition, they are qualified for over 500 temperature cycles from –40°C to 85°C.

Lower power consumption at colored applications

Another important advantage of LED is the low energy consumption.

The operating costs of colored LED`s are much less than that of corresponding conventional lamps, largely because of reduced energy costs. Incandescent bulbs convert the majority of power consumed in heat rather than in visible light. The efficiency of incandescent bulbs is about 5%. In addition, for colored applications, color filters are used to convert the white light in to the desired color. For red, filters cut almost 93% of the produced light. For the yellow signal the filter transmits only 15-25% of the light and the filter for the green signal only 9%, which reduces the efficiency of the system. By contrast, the amount of heat produced by the LED in Watt is trivial compared to a traditional bulb. LEDs are monochromatic light sources and emit light in narrow clearly defined parts of the visible spectrum. Thus, no filter is necessary to ensure a correct color. The efficiency of LEDs has tremendously increased in the past few years. Higher efficiencies are achieved through powerful processing and advanced technology, such as InGaAlP and InGaN materials. The yellow 590nm LED has an efficiency of 15lm/W, the orange 605nm LED has an efficiency of even 20lm/W.

Better light coupling properties in light guides because of special designed viewing angles

Caused by the radiation angle of LEDs, which is fixed by the package design, an ideal light coupling into a light guide gets possible. Through the small package design and the very good radiation angle the light coupling efficiency of LEDs is several times better than for conventional lamps. The viewing angle of TOPLEDs and SIDELEDs is 120°. With this radiation angle, a good coupling efficiency is reached and long hot spots are obviated.

Usage of SMD pick & place machines

OSRAM Opto Semiconductors SMD LEDs are mountable with standard high speed pick and place machines and standard soldering methods (like reflow of TTW-soldering). This causes cost reduction for PCB and mounting especially when other SMD components are getting assembled.

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About Osram Opto Semiconductors

Osram Opto Semiconductors GmbH, Regensburg, is a wholly owned subsidiary of Osram GmbH, one of the world's three largest lamp manufacturers, and offers its customers a range of solutions based on semiconductor technology for lighting, sensor and visualisation applications. The company operates facilities in Regensburg (Germany), San José (USA) and Penang (Malaysia). Further information is available at www.osram-os.com