1. Introduction

1.1. Background

Rising luminous fluxes of high-power LEDs as well as the growing energy consumption of lighting – 19 percent of the global energy production in 2006 [WT06] – have contributed to the widespread use of LEDs in modern lighting systems [St08]. Today, single LED-packages reach a light output that is competitive or even higher than those of incandescent- and compact-fluorescent-lamps, as illustrated in Figure 1-1. LED-arrays even surpass these values and achieve luminous fluxes of up to 9,000lm [Br11].

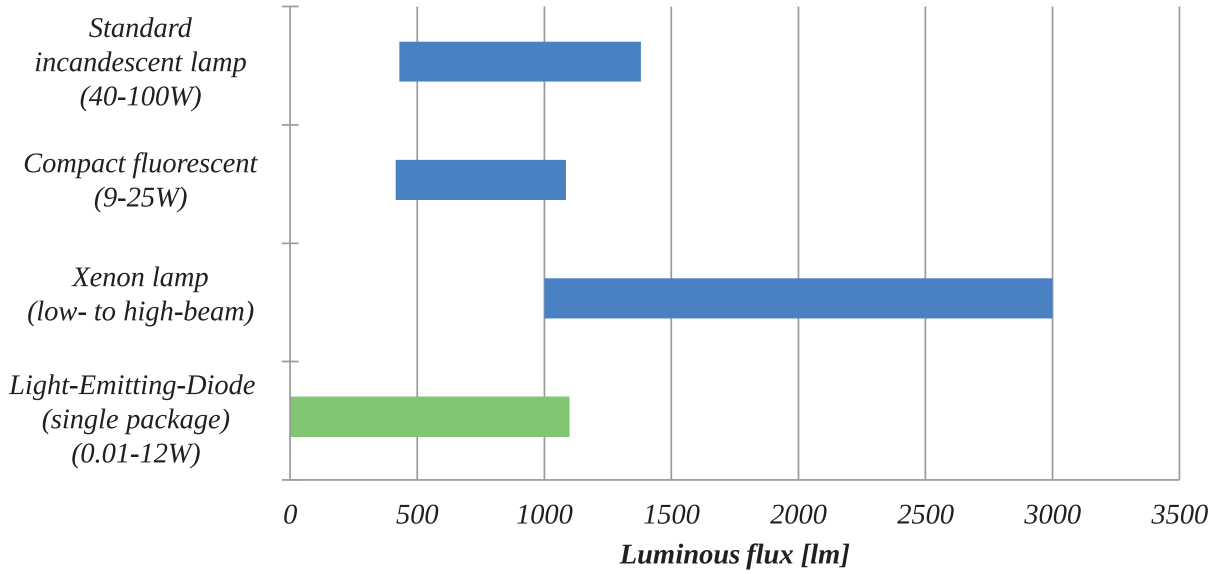


Figure 1-1: Total luminous flux of different light-sources derived from [WT06] with updated values for high-power LEDs [Os07], [Os08]

Increasing luminous efficacies, i.e. the emitted luminous flux per watt electrical power consumption, are another important reason for the growth of LED-lighting [Wh057].

The technological progress of LED-lighting can be seen from Figure 1-2, where a comparison of the luminous efficacy of different selected light sources is given. Currently, high-power LEDs achieve a maximum luminous efficacy of up to 157 lm/W, with a mean value of about 75 lm/W considering different power-classes [SSL11]. This is a factor 5 to 10 higher performance when compared to conventional incandescent- or halogen- lamps. Commercially available high-power LEDs can also compete with energy-saving- and fluorescent-lamps in terms of their luminous efficacy.

Furthermore, the general research goal for white high-power LEDs is set to reach 200 lm/W [SSL11] (single-chip LEDs), which is even higher than the efficacy of High-Intensity-Discharge lamps.

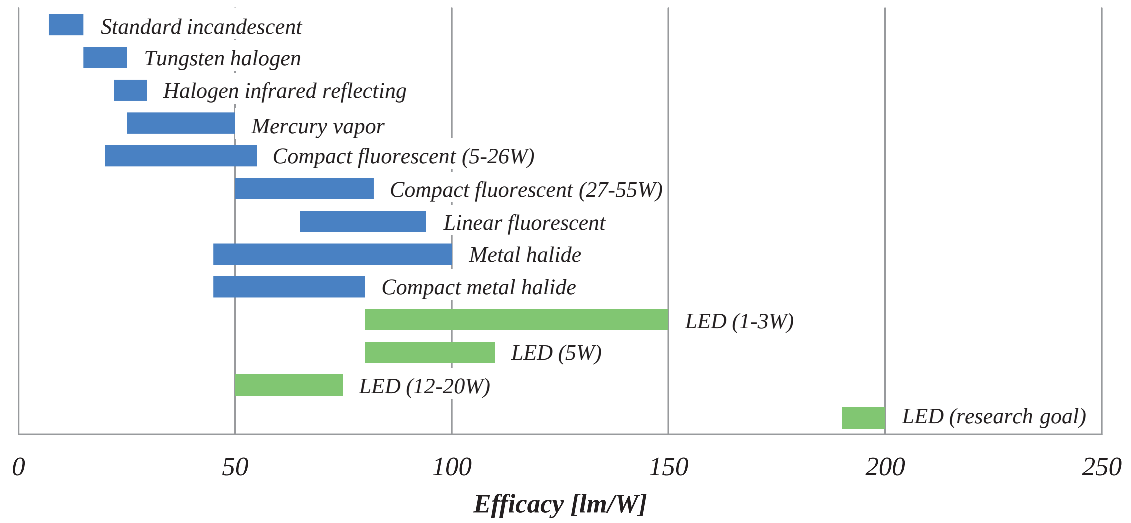


Figure 1-2: Luminous efficacy of selected light-sources derived from [AL03]with updated values for high-power LEDs [Os08], [Os07], [Ph07a], [Cr08b], [SSL11]

Another advantage of LEDs is their long lifetime which can reach a peak value of over 100,000 operating hours [Ph06] at optimal environmental conditions. Due to this, a multitude of lighting applications can be designed without considering maintainability. When combining this feature with the small geometrical dimensions of the LED-chips – a typical chip has an area of $A_{chip}=1\text{-}2mm^2$ – very compact or thin systems get possible.

These benefits as well as a wide range of available colours make LEDs and especially high-power LEDs the technology of choice for a multitude of applications. Besides, a large variety of customised lighting functions can be fulfilled by Solid-State-Lighting.

1.2. Applications of LED-lighting

LED-lighting applications comprise the automotive-sector, general-lighting and consumer electronics. These will be characterised in the following.

1.2.1. Automotive lighting

In the last years, LED exterior lighting has started to become a prominent innovation in automotive lighting. The beginnings have been already made in the 1990's with the introduction of the 'third stop-light' in LED-technology, where the fast turn-on behaviour of LEDs was used to decrease the reaction time of the following drivers [Ve06].

The use of complete LED taillights has been a further step to advance automotive exterior lighting. With the introduction of white light generated by LEDs and rising luminous fluxes, LED-based automotive front-lighting emerged and is already used in insular series applications today.

Besides to increased efficacies and lifetime, other technological benefits have contributed to the success of LED-lighting in automotive applications:

- The small footprint and height of LEDs allows new degrees of freedom in placing light elements and allows improved as well as complex three-dimensional lamp designs.

- LED-lighting systems often comprise a multitude of single LEDs, which can be individually arranged or electrically driven to enable new lighting functions highly exceeding the possibilities of conventional single and central light sources.

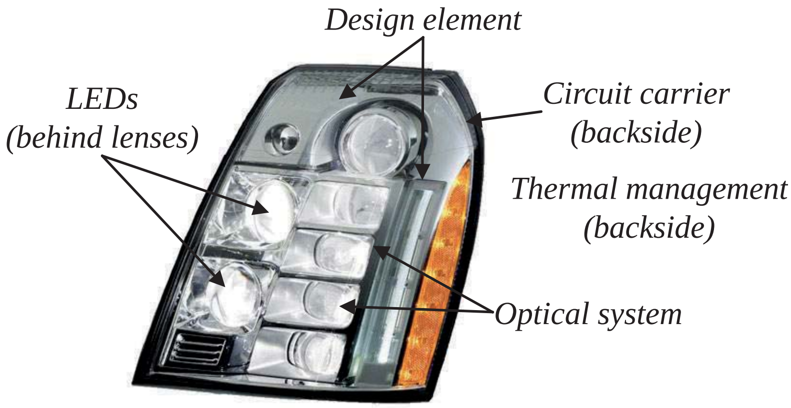
Figure 1-3 shows several examples of modern automotive LED-lighting systems which already benefit from the flexibility in lamp design obtained by the LED-technology. It is common to these solutions that the LEDs are spatially arranged in three-dimensions (*3D*) to create a more individual design of the day- and night-appearance of the automobile-front and -rear when compared to conventional halogen- or xenon-lamps. These systems will be called *3D LED-lighting systems* throughout this thesis.

(Source: Audi AG)

Figure 1-3: Trends in automotive exterior lighting: LED-lighting used as recognition feature to stand out from the competition and to differentiate model specific design

The arrangement of the LEDs is particularly used to underline the exterior shape of the automobile. The LED-design therefore provides a diversification in between the model-range of a car manufacturer. Furthermore, it is a recognition feature to stand out from the competitors.

Solutions with (advanced) *3D*-designs, however, require a complex assembly to mount and to electrically contact the LEDs in space that also comes at the cost of a large component count (Figure 1-4). Besides, conventional cooling solutions have to be adapted according to the desired *3D*-shape. Unfortunately, these aspects limit the design versatility that can be achieved in 3D LED-lighting systems and increase system costs when using state of the art assemblies. Therefore, the majority of contemporary automotive lamp designs are still focused on conventional shapes with single and central light source, as known for the past decades.



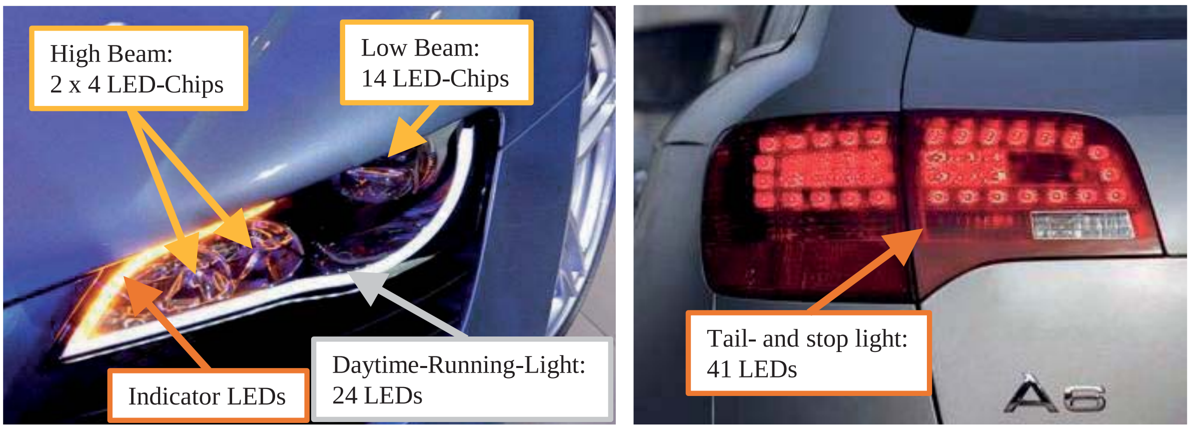
(Source: Cadillac)

Figure 1-4: Full-LED headlamp with limited *3D*-design

State of the art solutions for creating three-dimensional LED-lighting systems and their limitations will be discussed in detail in Chapter 2.

Environmental conditions and requirements

Automotive LED-lighting systems often consist of a multitude of LEDs that can have different power levels and colour values to perform lighting functions, like in stop-lights, day-time-running lights or even as low- or high-beam (Figure 1-5). The coloured and white LEDs are often located as clearly visible single light sources.



(Source: Audi AG)

Figure 1-5: Full LED-headlamp (left) and LED tail-lamp (right)

As the conventional 14V automotive electrical power net has a variable input voltage with typical values of V_{in} =8V-17V, a stable LED-brightness level has to be achieved over the entire input voltage range. Commonly, switched mode power converters are used to maintain and control the LED-brightness. When a large number of LEDs is used, a uniform brightness distribution is additionally required in order to maintain the required light output distribution as well as for optical reasons. In addition, brightness control is a key requirement in automotive lighting to provide basic lighting functions, e.g. day-time-running-lights are operated at night as position light which requires dimmed LED-operation. Finally, a high availability of the lighting system is required due to its security-related function. All these attributes define essential lighting functions, which require LED-drivers that are optimised towards automotive requirements.

3D LED-lighting systems further demand on solutions that allow the mechanical- and the electrical-connection of LEDs and LED-driver components in space to achieve the required design and functionality. As constructed space is limited in automobiles, the desired *3D*-shapes have to be realised without consuming excess space.

Harsh environmental conditions within the vehicle, with vibrations and shocks, amplify the requirements on the LED-lighting system. Furthermore, the LEDs and LED-driver components are excited to wide temperature ranges of -40°C to +80°C (up to +120°C in special cases) which requires an effective thermal management to keep component temperatures below critical values (Chapter 2). The heat dissipated by high-power LEDs increases temperature levels above environmental temperatures in the lamps. The electrical system should therefore operate at reduced losses when integrated in the lighting system.

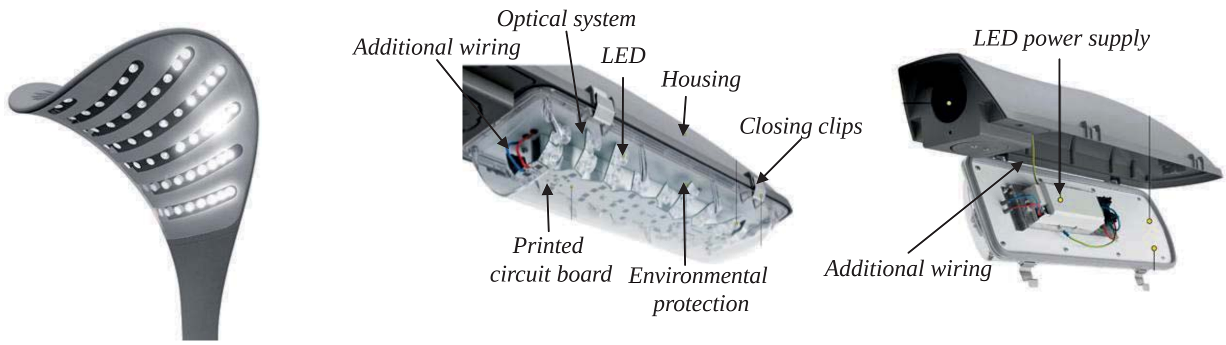
1.2.2. General lighting and consumer electronics

Next to the automotive environment, LED-lighting is increasingly used in general lighting and in consumer electronics. In the latter case, LEDs have been used as signal or control lights for decades, comparably to automotive (stop-) lighting. With rising luminous fluxes, however, also consumer articles emerged that contain high-power LEDs, e.g. in video projectors or in backlights of LCD-displays [Lu09].

The use of Solid-State-Lighting in general lighting has started to grow in the last few years. General lighting is considered in this thesis, as indoor- and outdoor-lighting, e.g. in street-lamps with LEDs that exhibit high luminous fluxes of 2,000-10,000 lumens [Ca09], [PT096], [Ow096]. The resolution of the European Commission for phasing out incandescent lamps and of lamps with a non-tolerable luminous efficacy [Eu08] further accelerated the demand on high-power LEDs as an alternative light-source in general lighting.

Like in automotive applications, in general lighting or in consumer electronics LEDs are not only used for reasons of saving energy and for lifetime considerations. Moreover, there are some applications that benefit from LEDs' small footprints and the ability to spatially arrange individual light sources. Figure 1-6 (a) shows an LED street lamp with a three-dimensional design as one possible example. In this lamp, the LEDs are used to create a completely new design which allows a diversification among other street lamps, which is comparable to the approaches in the automotive segment. Further, a three-dimensional LED-arrangement can also be used to obtain an improved brightness distribution on the street (Figure 1-6 (b)).

In contrast to the automotive sector, in consumer electronics or in general lighting, there is no general trend towards three-dimensional shaping of lighting systems, due to the wide span of applications, which neither require enhanced shaping possibilities nor need to save construction space.



(Source: Siteco GmbH) (Source: Schréder GmbH)

(a) (b) (c)

Figure 1-6: Three-dimensional shaped LED streetlamps

The absence of a simple solution for forming 3D LED-lamps and the high assembly complexity – with a large number of components (Figure 1-6 (b), (c)) – further contributes to the low number of applications, which benefit from a three-dimensional alignment of LEDs up to now.

Environmental conditions and requirements

General lighting solutions often comprise a multitude of high-power LEDs to meet the requirements on high luminous fluxes, as shown in Figure 1-6. Also consumer electronics, like the background illumination of flat-screen TVs, contains a large number of LEDs. A power electronic system is therefore required to maintain required LED-brightness-distribution and -control, e.g. for dynamic background illumination [WKM09]. Further, in 230 VAC mains application systems, galvanic isolation is required to decouple high input voltages from the LEDs. This is especially necessary when a compact lamp-design without extra LED-housing is desired. Hence, a power converter is required to transform high ac voltages into appropriate dc voltages for the LEDs.

Different environmental conditions, e.g. ambient temperatures, have to be considered in domestic applications, depending on indoor- or outdoor usage. In the vast majority of applications, the environmental impacts are significantly lower than in automotive LED-lighting. It is therefore assumed that most of the foregoing environmental conditions are also covered by the demands of automotive exterior lighting.

Thus, the automotive environment, with its conventional 14V automotive electrical power net, will be the considered environment in this thesis. However, special applications suitable for the mains will be commented throughout the work when applicable.

1.3. Requirements on three-dimensional LED-lighting systems

Progresses in the LED technology have led to a variety of applications in automotive- and general-lighting. Especially the field of automotive exterior LED-lighting uses the small footprint of LEDs and their characteristic as point light sources as key features to combine lighting tasks with design (Section 1.2).

Although automotive LED-lighting is at the leading edge regarding three-dimensional lighting solutions, the current construction of 3D LED-lighting systems is not optimised towards complex design requirements. Contemporary assemblies require a large number of construction parts to perform *3D*-contacting and -mechanical fixation of LEDs and their related power electronic LED-drivers.

Thus, the plurality of automotive LED-lighting systems is still focused on conventional designs of front- and tail-lights, as known for decades. The same limitation has been observed for the majority of LED-based general-lighting systems.

To improve 3D LED-lighting systems, the following target functions can be identified and should be addressed:

- *Spatial und mechanical functions:*
    - The lighting systems must be able to follow complex three-dimensional shapes to further improve the degrees of freedom in the lamp design. For this reason, the LEDs and the power electronics, for their electrical drive, require a *3D*-structure which fixes them.
    - Due to the requirement of reduced constructed space (automotive), the system should also be able to achieve the required *3D*-shape at a minimum of excess volume. Hence, solutions which allow a reduced construction height are desirable.
    - The systems should be built at a reduced number of components to reduce efforts in their spatial fixation. Furthermore, they must be robust against application specific environmental conditions, e.g. vibrations or maximum temperatures.
- *Electrical functions:*
    - In 3D LED-lighting systems, the LEDs and the power electronics must be electrically contacted in three dimensions and the appropriate signals have to be delivered to the spatially distributed LEDs.
    - The electrical drive has to ensure that a homogeneous brightness distribution is achieved among the LEDs, as they are often clearly visible as single light-sources. Here, LED specific requirements concerning temperature- and electrical-behaviour (Chapter 2 and 4) have to be observed.
    - As input-voltage levels can vary, the LED drive has the function to keep stable LED brightness levels over input voltage variations. Furthermore, the power electronics should provide a galvanic isolation when high (input-) voltages appear to separate them from the remaining system.
    - (Automotive) illumination requires high system availability. Therefore, the LED-driver should be able to maintain a high operational availability even at LED failures.

- *Thermal functions:*
    - An effective cooling of the used high-power LEDs and the power electronic components, especially for high power levels, is required and has to take care of the demand on high degrees of freedom in *3D*-design.

1.4. Problem description

The high versatility in placing individual and compact light sources is a key feature provided by LED-lighting technology. It allows an enhanced design flexibility which can skilfully be used to improve the appearance, but moreover to enhance functions of modern lighting systems, as introduced in Section 1.2. So far, the LED-technology's potential for improving three-dimensional designs is, however, insufficiently used in the vast majority of LED-lighting applications.

The physical realisation of contemporary LED-lighting systems requires a large number of components and is identified as the main hurdle for limiting the distribution of 3D LED-lighting systems. These systems comprise LED-drivers, *3D*-mounting and -contacting components as well as thermal management structures that have to be mounted and arranged in three-dimensions leading to high efforts and costs (Section 1.2).

A new approach is therefore needed for the realisation of 3D LED-lighting systems to decrease the number of components and to enhance the design versatility. This directly addresses the components which are necessary to fulfil spatial-, electrical- and thermal-functions, defined in Section 1.3.

Determining a new concept for the realisation of 3D LED-lighting systems requires the analysis of the current practice and evolution of 3D LED-lighting assemblies to identify the main technological boundaries as well as to derive requirements on future assemblies.

The main objective in this concept, and hence in this thesis, is to decrease the number of components of contemporary automotive LED-lighting systems and to enhance the design versatility in three-dimensions by integrating the functions provided by individual parts into one or more multifunctional components. This concept requires the investigation of the integration potential for the LED-driver, for the electrical- and spatial-contacting and for the thermal-management in the '3D multifunctional-component(s)'.

As a wide range of applications, with different spatial arrangements and power levels, exist for LED-lighting it is further required to provide techniques that derive the limitations and possibilities for the concept's electrical-, spatial- and thermal-design. These parameters can be used to determine the feasibility of prospective applications and to derive adapted designs.

1.4.1. Derived objectives

Analysing the foregoing problem description, the main objective of this thesis is to:

> *decrease the component number required in high-power 3D LED-lighting systems with power electronic LED-driver to reduce the complexity in the assembly and to increase the degrees of freedom in the design.*

To achieve this aim the following objectives have to be determined:

- Identification of the main reasons that limit enhanced designs of contemporary high-power LED-lighting systems by analysing the present practice of construction and the evolution towards 3D LED-lighting systems

- Determination of an approach to use the technology of 3D-Moulded Interconnect Devices (3D-MID) for enhancing the *3D*-design whilst decreasing the construction complexity of high-power LED-lighting systems with LED-driver by increasing the level of function integration

- Development of optimised LED-drivers with integrated lighting functions for a simplified 3D-MID realisation

- Determination of merits and limitations to mount and contact the LED-driver and the LEDs on the 3D-MID as well as to analyse influences of the 3D-MID technology on the spatial- and electrical- realisation of power-electronics

- Examination of the potential to integrate thermal management functions into the 3D-MID for low complexity systems and to derive a solution to enhance the power level of 3D-MID-based LED-lighting systems whilst maintaining high degrees of freedom

1.5. Thesis layout

Figure 1-7 visualises the layout of the thesis.

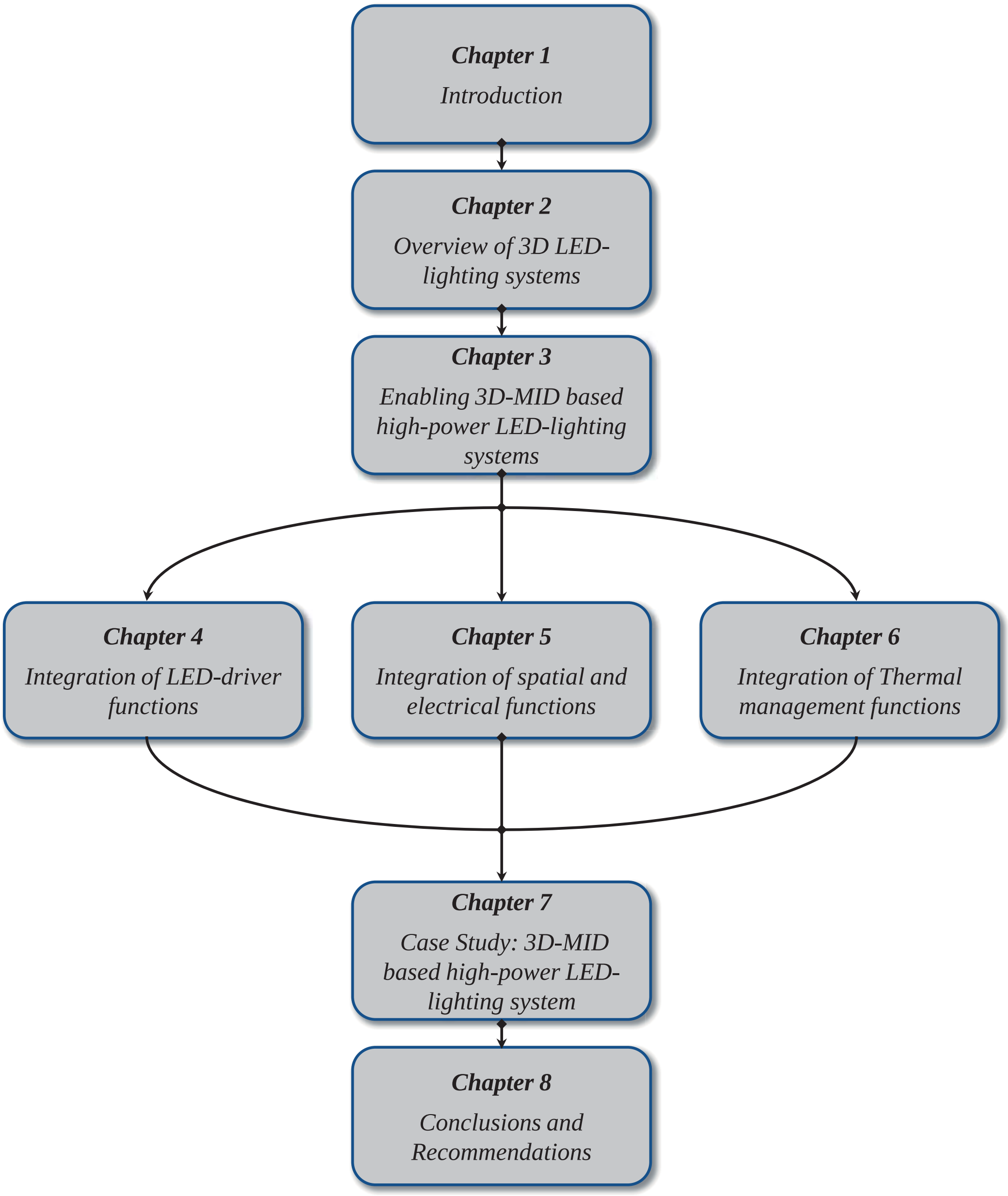


Figure 1-7: Thesis layout

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2. Overview of three-dimensional LED-lighting systems

2.1. Introduction

Chapter 1 has shown that enabling LED-lighting systems with an enhanced three-dimensional shape for improved design and functionality is the core topic of this thesis. The main limitations of contemporary assemblies – namely the limited degrees of freedom and the multitude of components needed – have been indicated.

In this chapter an overview of the essential components found in state of the art LED-lighting systems is given with a focus on the required power electronic system (Section 2.2). This includes the components' technological requirements as well as functions that they have to fulfil.

The technical evolution towards three-dimensional LED-lighting is outlined in Section 2.3 and gives an overview of how contemporary LED-lighting assemblies are able to create *3D*-structures.

The technological hurdles but also potentials, identified in Section 2.3, are used in Section 2.4 to derive requirements which should be fulfilled for making enhanced three-dimensional design and versatility in future LED-lighting systems possible.

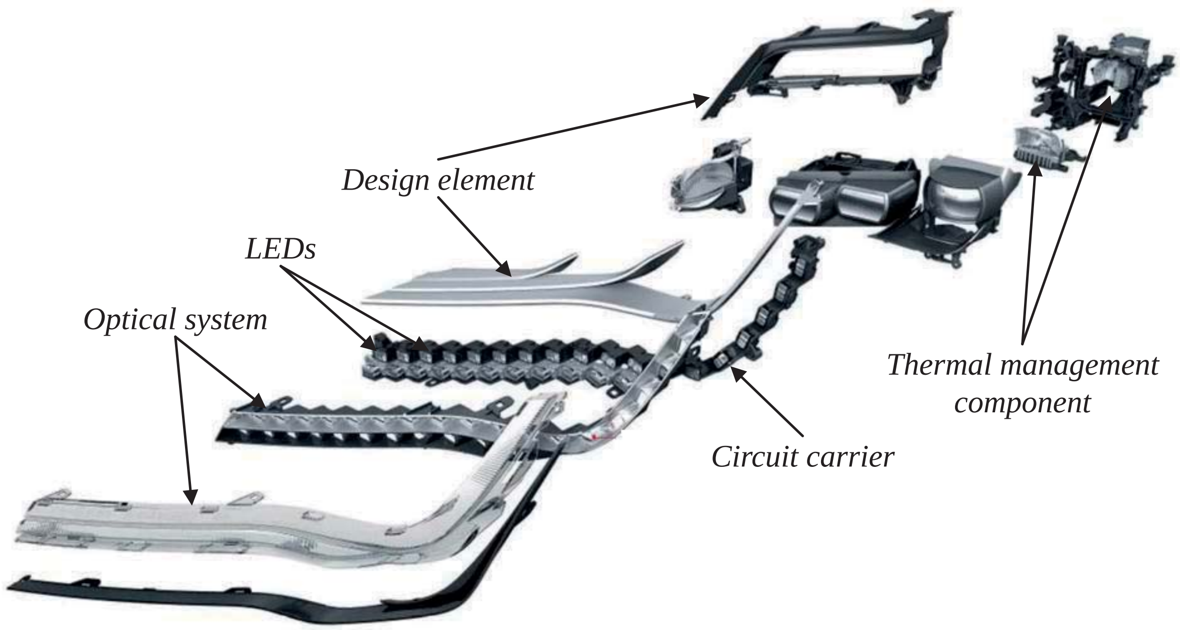
The chapter will be summarised in Section 2.5.

2.2. LED-lighting systems: components and functions

Modern LED-lighting systems comprise a variety of components that are required to fulfil lighting functions, as already introduced in Chapter 1. Figure 2-1 shows an automotive LED-lighting system used in front lighting, visualised in an exploded view. In this system, all light-functions are realised with LED-technology.

It can be seen from the figure that a multitude of LEDs, circuit carriers for their electrical interconnection, external thermal management and optical components as well as several design elements are required to build high-power LED-lighting systems. The housing and the LED-driver complete the system, but are not shown in this view.

In contrast to the vast majority of (power) electronic systems, LED-lighting devices usually contain the LED-driver as well as the load – the LEDs – in the same enclosure and they are often also attached on the same circuit carrier. The electrical and thermal behaviour of the LEDs, e.g. regarding power losses, has therefore to be considered in the design of the power electronic system. Moreover, the planned design – including the number and size of the LEDs – defines the lamps' power level as well as the component positions in three-dimensional space.



(Source: Audi AG)

Figure 2-1: Example: exploded view of automotive front LED-lighting system (Source: AUDI AG)

It can also be deduced from Figure 2-1 that a variety of functional interdependencies appear in LED-lighting systems. For example, the electrical system containing the LED-driver, the LEDs and the circuit carrier is mechanically attached to thermal management components. A part of this structure is further connected to the optical system, and so forth. This leads to a complex combination of single components that are often individually constructed; this challenges the assembly of the final three-dimensional LED-lighting system.

In the following, relevant components of LED-lighting systems with LED-driver will be explained to give an overview of their main functions and requirements. The overview includes the LEDs, the LED-driver, the thermal management components as well as the circuit carrier technology. These components build the “electronic system” in the LED-lamp.

The housing and the optical components will not be discussed further here, as their implementation is out of the scope of this thesis.

Detailed investigations on each domain of the electronic system will be individually performed in Chapters 4-6 to enhance the degrees of freedom of future 3D LED-lighting systems.

2.2.1. Light-Emitting-Diodes (LEDs)

LEDs play a central role in the realisation and assembly of LED-lighting systems. As Light-Emitting-Diodes and their high-power derivatives show a highly different optical, thermal and electrical behaviour compared to incandescent lights a short summary of state of the art LED characteristics and requirements concerning the power electronic system will be given in the following.

The thesis' focus lies on white high-power LEDs, as these build the cornerstone for using LEDs in general lighting, e.g. in automotive- or domestic-applications. White light can be created by three different methods using the LED technology [Sc03]:

- **Multi-colour LEDs** can be used to obtain white light by mixing the emission spectra of the individual LED (-chips).
- **Wavelength converters** use ultraviolet or blue LEDs attached with several layers of different phosphors. As a result of this combination, white light is excited. For this reason, the LEDs are also-called Phosphor-Coated (PC-) LEDs.
- **Semiconductor converters** use a primary light source, e.g. a blue LED chip, and an additional active semiconductor region that absorbs a fraction of this optical power and re-emits photons with a longer wavelength. As a composition white light is emitted.

The wavelength-conversion is the most common and widely distributed approach to create white light. This is mainly determined by cost reasons, the simplified drive of single LED-chips and the comparably stable colour values of phosphor-coated LEDs [Sc03], [BSS06]. Hence, general illumination applications and automotive (front) lighting use these types of LEDs and will therefore be focused on in this work.

LED power level

Light-Emitting Diodes are used in a variety of application fields and cover a wide range of light output levels and a variety of colours, as already shown in Chapter 1. Next to the light output, also the power level can be used as criteria to diversify LEDs. Besides it is an important figure to determine the electrical design of the LED-driver as well as for the implementation of an effective thermal management. The latter is linked to the electrical LED-efficiency which shows typical values of *15-20* percent for high power LEDs [QLH09]. The remaining power is dissipated as heat and has to be effectively cooled in the LED-lighting system.

Figure 2-2 gives an overview of common LED power levels with related drive currents, luminous fluxes and typical LED-packages of each power-class. The overview divides the LEDs into three classes that will be referred to subsequently in the thesis:

- **Low-power LEDs** with a power consumption of below $P_{LED}=0.3W$
- **High-power LEDs** comprise power levels of $P_{LED}=0.5\text{-}3W$ as a typical indication of size
- **Ultra high-power LEDs** are mainly realised by combining several high-power LED-chips in a single package, leading to power levels $P_{LED}>3W$ and luminous fluxes of 1000 lumens out of one LED package and higher [Os08].