

High Power Solid State Retrofit Lamp Thermal Characterization and Modeling

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Abstract. *Thermal and thermo-mechanical modeling and characterization of solid state lightening (SSL) retrofit LED Lamp are presented in this paper. Paramount importance is to design SSL lamps for reliability, in which thermal and thermo-mechanical aspects are key points. The main goal is to get a precise 3D thermal lamp model for further thermal optimization. Simulations are performed with ANSYS and CoventorWare software tools to compare different simulation approaches. Modeled thermal distribution has been validated with thermal measurement on a commercial 8W LED lamp. Materials parametric study has been carried out to discover problematic parts for heat transfer from power LEDs to ambient and future solutions are proposed. The objectives are to predict the thermal management by modeling of LED lamp, get more understanding in the effect of lamp shape and used materials in order to design more effective LED lamps and predict light quality, life time and reliability.*

Keywords

Light Emitting Diodes, SSL lamp, thermal validation, thermo-mechanical modeling.

1. Introduction

Solid-state lightening (SSL) is a rapidly developing technology that has substantial headroom for continued evolution. In the last few years the use of LED (Light Emitting Diode) lamps has been growing almost exponentially [1-3]. First commercial prototypes of 600 lm LED lamps were presented in recent times to substitute traditional incandescent light bulbs. At present, light bulb manufactures are moving to the environment friendly technology, without any toxic materials, that results replacement of classic incandescent lighting even faster than expected [4]. Moreover, classical light bulbs (60 W and above) are not permitted to be sold any more in many European states.

The demand of higher efficient systems and the LED technology growth have favored huge expansion. In this

consequence, it is essential to design new high power lamps for reliability. The key points which influence the reliability most is thermal and thermo-mechanical aspects. In today's high-power LED applications, these aspects must be taken into account to predict light quality, life time and reliability of LED lamps. In such applications, the substrate on which LED devices are soldered (LED board) can become a critical part.

Critical parts of LED lamp have been defined by a precise 3-D modeling of LED lamp where the most attention has been paid to LED board itself. In such evaluation processes, the main objective is to keep the thermal stresses as low as possible for the widest temperature range and another objective is to determine the number of thermal stress cycles that could lead to the LED board failure due to thermal fatigue.

Heat dissipation and LED temperature were not a problem when low power LEDs were used. However, in today's high power LED applications thermal management issues must be taken into account [1] to ensure light maintenance and quality, life time and reliability of LED lamps. Lamp materials and electronics components can age at high operational temperature affecting light output [2]. However, the most important objective in LED thermal management is to limit the temperature of LEDs and solder connections. These parts are usually the most critical for the useful lifetime of the LED lamp. Contrary to the conventional lighting, LED lamps in general don't fail catastrophically. As light output is a function of temperature and time, the light output ordinarily decreases to an unacceptable level in time.

The main goal in LED lamp design is to transport the heat from the high power LED through substrate and board, thermal interface material (TIM), heat sink and bulb material to the environment. The outer surface of the LED lamp is then another critical part of the cooling system.

2. LED Lamp FEM Model

An important aspect in 3D FEM simulation is the conception of the geometric model. The geometry and

shape of realistic LED lamp is intrinsically complex. In our case the model is composed by many different materials and regions. A complete three-dimensional model of retrofit 8W LED Lamp has been designed for Finite Element Method (FEM) simulation with all necessary details (Fig. 1). The model represents a retrofit LED lamp including six high power blue LEDs mounted on PCB board. LED GaN wafer is mounted on Al₂O₃ package that includes one thermal Cu pad and two electrical pads. On each of the LEDs package a small silicon lens is placed in order to get a wide angle light beam (Fig. 2).

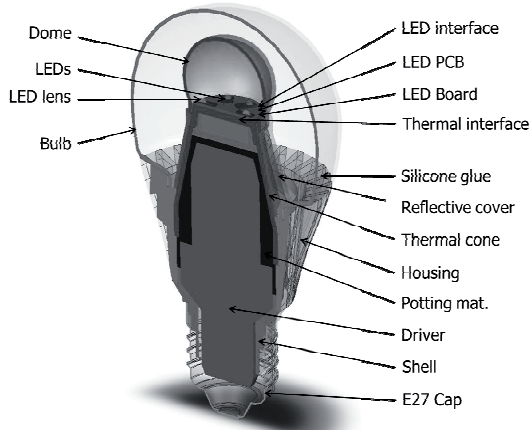


Fig. 1. SSL Lamp 3-D model includes sixteen different compact parts. Air inside light bulb and inside light conversion dome was included to the model.

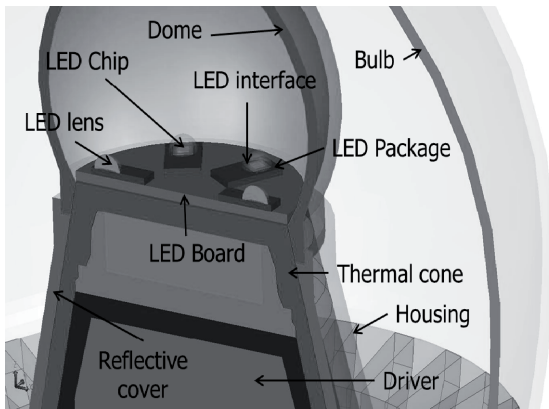


Fig. 2. Detailed view on LED board placed on aluminium alloy thermal cone. The board includes six LED with Al₂O₃ package and LED chip.

High power LEDs are typically based on GaN solid state semiconductors and emit light in a narrow blue range of the visible spectrum. Blue light must be adapted by luminophores into white or yellow-white light spectrum, which is close to spectrum of incandescent light bulbs. The light conversion can be made by a polycarbonate spherical dome containing phosphors which is mounted on top of LED board. The dome is needed for blue light (produced by GaN LED) to yellow-white light conversion (Fig. 2). The model contains also an electronic driver board, a thermal cone and housing (heat sink). Other details as E27 cap, shell, potting material, reflective cover mounted on thermal

cone, driver support and thermal interface layer between LED board and aluminum alloy thermal cone are also included in the model Fig. 1.

One important aspect of three-dimensional finite element simulation is mesh generation since it affects the accuracy of the final results. The LED lamp FEM model mesh is designed suitably fine in order to have acceptable accuracy. Because of the non-orthogonal parts in the model, tetrahedron elements are used to merge and extrude all layers in order to produce a continuous mesh. To reduce the number of nodes, and therefore the computing time, the element distribution is adapted to the shape of the bodies; the number of elements is increased to capture small features in the model. The designed model contains approximately 490,000 nodes.

3. Material Properties of LED Lamp

The validity of simulation results are limited not only by precision of 3D model and its mesh, but also by the accuracy of the material properties data. Twelve different materials are combined in the LED lamp simulation model. Thermal and mechanical coefficients for each of these materials were taken from different sources [6-13]. Moreover, in some cases material properties are not defined consistently for all sources. Different sources refer to not the same values for given material properties. To resolve this difficulty, the average value of the given material quantities has been used.

Material	Thermal parameters		Mechanical parameters			References
	Thermal Conductivity λ [W/mK]	Specific heat C_p [J/kgK]	Thermal expansion α [e-6/K]	Young's modulus E [GPa]	Poisson ratio ν [-]	
GaN	130	490	5.6	200	0.4	5, 10
Aluminum alloy	100	880	23.4	70	0.3	12
Copper	400	385	17.0	110	0.4	12
Brass Ni	122	380	20.0	100	0.3	11, 13
Glass	1.10	840	8.0	70	0.3	11, 12
Polycarbon	0.20	2000	50.0	5	0.3	6, 8, 11
Silicone	0.22	1460	220.0	1	0.5	6, 7, 11
Silicone filler	2.00	1460	220.0	1	0.5	9
PBT	0.27	1700	25.0	9	0.3	11, 13
Polyamide6	4.0	1130	40.0	15	0.40	11, 13
FR4	4.0	1085	23.4	70	0.3	12
LED board	40	1085	23.4	70	0.3	Estimated

Tab. 1. SSL Lamp thermal and mechanical material properties used for LED lamp simulation.

The thermal and mechanical material properties used for the modeling of the LED lamp are summarized in Tab. 1.

4. Thermal Modeling

To obtain and compare steady state and dynamic thermal distribution of LED lamp ANSYS and CoventorWare finite element simulation tools have been used.

The initial and boundary conditions must be specified with care because these conditions can have an influence to calculated results precision. For the thermal analysis of the LED lamp, the essential boundary conditions are: heat generation caused by Joule heating in all electrical parts, heat generation produced by light loses in light conversion dome and in light bulb, heat convection on outer parts and radiation. Radiation effect is determined for all model faces that are in contact with air.

Heat generation in LED lamp take place in LED driver 1.2 W (measured value), in six LEDs 4 W (calculated from datasheet) and in polycarbonate light conversion dome 1.5 W (evaluated by optical measurement).

With both ANSYS and CoventorWare a thermal analysis is performed to calculate the spatial temperature distribution and steady state heat flux.

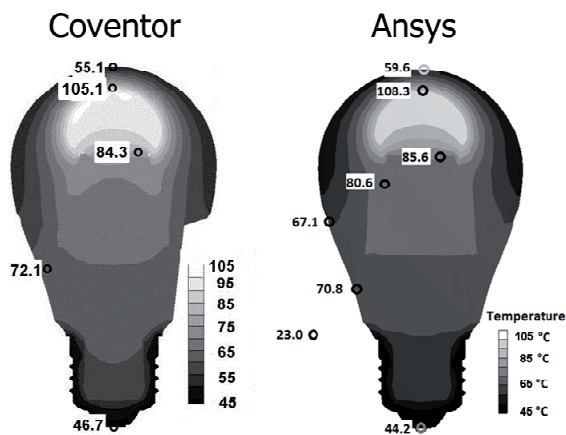


Fig. 3. Computed steady state thermal analysis temperature distribution. Comparison between Coventor and ANSYS simulation tool is shown.

Thermal convection coefficient ($5 \text{ W/m}^2\text{K}$) was prescribed for all outer parts of LED lamp that are in interaction with the air. This value can be set for cases, where air velocity is small (under 0.05 m/s) [11]. Radiation affect to ambient (temperature of 22°C) was also taken into account for all inner and outer parts of the lamp which are exposed to air. Emissivity coefficient is different for diverse materials and must be appropriately set for all used lamp components [13]. Simulation results can be approved in the future using the ANSYS-CFX thermal simulation, which take into account natural air allowing convective air flow inside bulb and dome and also around the lamp.

In Fig. 3 the calculated temperature distribution results for Coventor and Ansys are compared. Temperatures at defined locations were sampled to compare results from two different simulation tools. Fig. 3 shows calculated temperatures for bulb, dome, LED, thermal cone and housing. The LED temperature is defined here as the maximum temperature that occurs in the GaN LED die. The model is not complete to be able to calculate the LED junction temperature, but is adequate to calculate a LED GaN die temperature. The calculated LED die temperature is 84.3°C for Coventor simulation and 85.6°C for the ANSYS simulation which shows good agreement.

Because reliability and life time of LED chip mostly depends on working temperature [5], we proposed alternative materials replacement to improve heat conduction to ambient which leads to decreased LED die temperature. To predict an effect of material thermal conductivity, material parametric analyses was carried out to investigate future thermal management improvements with respect to materials. The influence of the thermal conductivity of the housing (heat sink) material on the most relevant temperatures is depicted in Fig. 4. It can be seen that if aluminum is used for housing (heat sink) instead of polyamide 6, the LED temperature will drop about 6°C . The LED die temperature can be also decreased by optimizing of heat sink shape and number of fins.

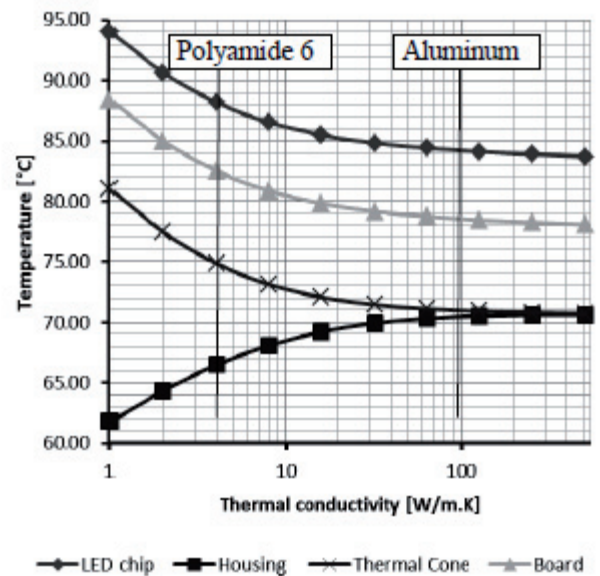


Fig. 4. Housing (heat sink) thermal conductivity parametric study. Thermal conductivity was swept in range from 1 to 500 W/m.K . The figure shows temperature difference for polyamide 6 (used in the measured LED lamp) and aluminum.

5. Thermal Stresses Analysis of the LED Board

Thermal stresses, which are caused by thermal expansion of the used materials, are important for the reliability

and life time of LED board. Especially in systems composed from different materials where thermal cycling appears in broad temperature range. To get realistic result from thermo-mechanical modeling, a LED board model was designed with all LED parts, mounting pads, thermal interface materials, metallic leads and thermal vias placed in FR4 board under each LED package (Fig. 5).

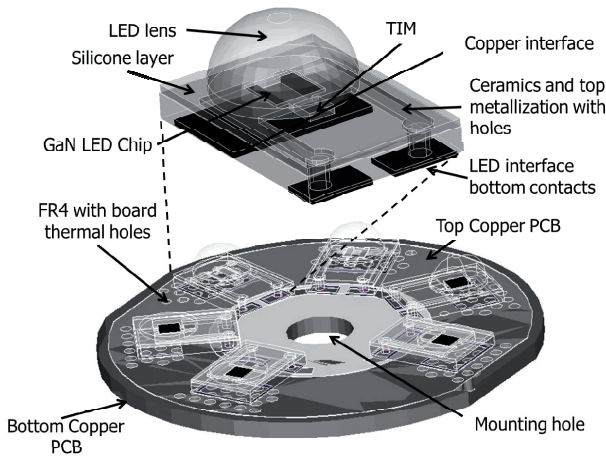


Fig. 5. 3-D model of LED board used thermo-mechanical modeling. Board includes six packaged LED models including LED lens.

To calculate accurately deflection and stresses induced in the LED board and its components by the thermo-mechanical FEM analyses, parabolic 10-node elements are used for model mesh [12]. Mounting hole inner face nodes are mechanically fixed. This boundary condition reflects a fact that the LED board is mechanically mounted on the thermal cone by a central screw assembly. All other nodes and faces of the model can freely move in all three directions. The LED board was placed on thermal cone to insure realistic temperature distribution on bottom side of the LED board. Zero stress temperature was defined for soldering materials according to technology process used.

Simulation was performed for three most interesting temperature cases, e.g. room temperature (23 °C), extreme storing temperature (-40 °C), and at working temperature where heat generation of 4 W is applied in the LEDs. The equivalent heat flux through the bottom and side wall of the thermal cone has been taken from the thermal analysis of the LED lamp model. Convection (5 W/m²K to air) and radiation has been prescribed on the top surface of board and LEDs.

Initial simulation based on mechanical material properties where only Yong modulus and Poisson ratio was taken into account extent plastic deformation (yield stress) in some regions. To overcome this inaccuracy and get more exact results, the plastic behavior of all materials has been taken into account. In order to correctly simulate plastic behavior of the board model, a stress-strain curve must be defined for all used materials. Moreover these stress-strain curves are in some cases heavily temperature dependent.

Fig. 6 shows the calculated residual stress distribution based on a linear elastic approach for room temperature (23 °C) and for working temperature where temperature distribution on the board is given by dissipated power in LEDs. The biggest residual stress can be found in LED chip (~139 MPa) and in solder joint (72 MPa). Mechanical stresses increase as ambient temperature decreases. This effect is given by zero stress temperature which is defined by soldering process (220 °C).

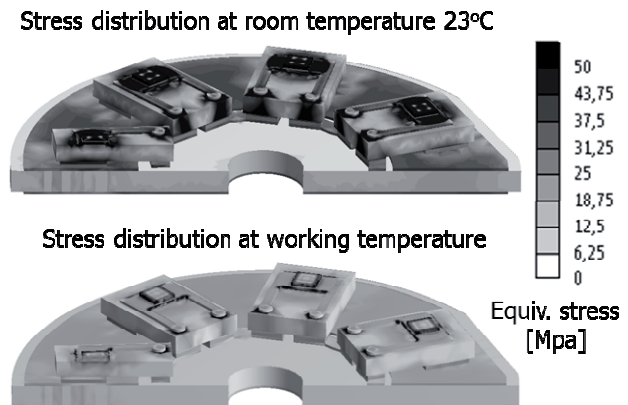


Fig. 6. Residual stresses of the LED board. The top picture shows the stress distribution at room temperature. The bottom picture shows the stress distribution at working temperature that is defined by heat dissipation in LEDs.

6. Thermal Validation and Measurement

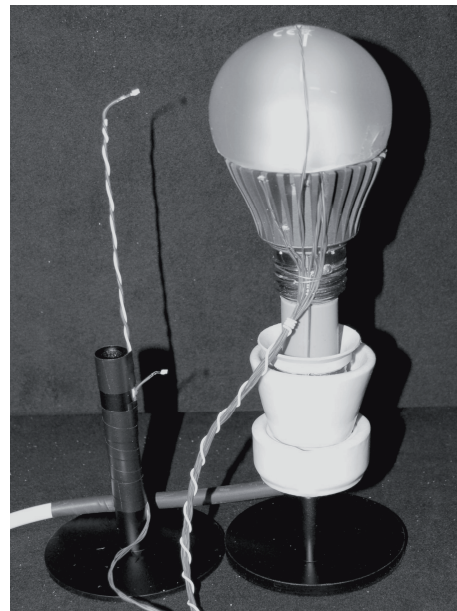


Fig. 7. Measurement setup. The LED lamp is placed in the thermal chamber. Wires lead to temperature sensors placed inside and outside of the lamp. Temperature sensors measuring ambient temperature are also clearly seen (left).

For validation of the thermal modeling a laboratory measurement test set-up was prepared. The LED lamp was placed in reflection-less thermal chamber (Fig. 7). The test set-up is performed in a room with air temperature control (23°C). Thermal measurement was carried out by two independent methods. In the first method, the temperature is measured as a function of time at several LED lamp locations on inner and outer parts of the lamp using SMD PT 1000 micro-scale temperature sensors (Fig. 7 and 9a). Temperature sensors are placed on the LED board, thermal cone, heat sink, top of the dome and top of the lamp. Also the ambient air temperature in the temperature chamber was measured.

Fig. 8 shows the results of the temperature transient measurement with temperature sensors. A steep temperature growth is observed at the beginning of the test. Within 2 hours the temperature reaches a steady-state situation. In Fig. 8 the results of the previously mentioned steady-state simulation are presented and marked by symbols at time 8000 s where temperature transient has already reached steady state.

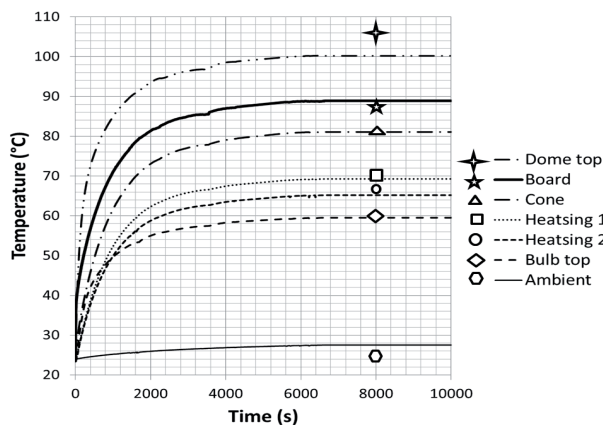


Fig. 8. Measured (line) and calculated (symbol) temperatures of the LED lamp.

The temperatures calculated by ANSYS and Coventor underestimate slightly the measured temperatures of LED board (85.6 °C ANSYS simulation, 88.9 °C measurement). The underestimation might be due to the use of estimated heat generation input and a too high emissivity coefficient. The biggest temperature difference (8.1 °C) between simulation and experiment is detected for the dome temperature (108.3 °C ANSYS simulation, 100.2 °C measurement). The higher calculated dome temperature might be caused by not modeling the air flow inside a dome and inside the bulb, which could in reality cool down the surface of the dome. In additional measurements, radial temperature dependence was found in the LED board with the lowest temperature in the middle of the board.

The second measurement method uses a thermo camera imaging to obtain temperature distribution of the LED lamp. In this measurement method, the emissivity coefficients must be known for all materials. To overcome a problem with different emissivity of diverse materials,

a black strip was made on each measured LED lamp part. The temperature is then sampled on the black strip, which has the same emissivity for all materials. Fig. 9b shows the temperature distribution sampled by thermo camera with marked measuring points. In order to similarly sample the temperature distribution inside the lamp, the glass bulb was dismounted. Correspondingly, for board temperature distribution measurement the light conversion dome was dismounted.

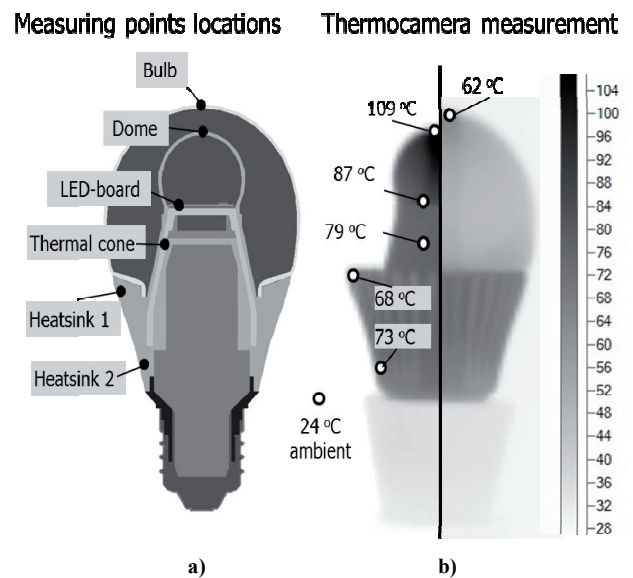


Fig. 9. a) Thermal sensors location used for temperature measurement and comparative temperature samples from simulations. b) Temperature distribution sampled by thermo-camera. The left side shows the thermal distribution under glass bulb. Temperatures are sampled in defined locations shown in Fig. 9a.

7. Conclusions

Thermal performance of an 8W LED Lamp was analyzed by two independent simulation tools (CoventorWare and ANSYS) and validated by two thermal measurement methodologies. All modeled and measured results are compared in Tab. 2. Achieved results are in good agreement; simulated temperature of the LED board is slightly underestimated while simulated temperature of the dome is higher than measured. Enhancement of the simulation model and more accurate heat generation value will results an improved calculation of the temperatures. An interesting result can be found in temperature distribution of the LED lamp: the hottest component is not LED chip itself, but the top of light conversion dome.

With these calibrated 3D models, the critical parts can be determined when designing higher power LED lamps. In addition, solutions for thermal problems that came up from higher power input were explored.

Critical parts have been determined by thermo-mechanical modeling. High mechanical stress was located

in solder joints between LED package and LED board. Better mechanical design of LED board could result better reliability and life time which is key issue in high power LED lamp design.

	Temperature (°C)			
	Simulation		Measurement	
	ANSYS	COVENTOR	Temp. sens.	Thermocam
Bulb top	59.6	55.1	59.5	62.0
Dome top	108.3	105.1	100.2	109.0
Board	85.6	84.3	88.9	87.0
Cone	80.6	79.8	81.1	79.0
Heatsink 1	67.1	68.8	65.2	68.0
Heatsink 2	70.8	72.1	69.3	73.0
Ambient	23.0	23.0	25.7	24.0

Tab. 2. Comparison of calculated and measured temperatures in the LED lamp. Sampling locations are shown in Fig. 9a.

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