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Waste heat recovery in solid-state lighting based on thin film thermoelectric generators

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ABSTRACT

The waste heat of high-power light emitting diodes (LEDs) is well localized and can be efficiently harvested in contrast to incandescent or fluorescent light sources. Compact thin film thermoelectric generators can accumulate the high-density heat flux from the LED chip and convert it into usable electrical power. We designed and analyzed a thermal management setup with high power LED and embedded thin film thermoelectric generators. The available thermal gradient of approximately 50 K allows conversion of the LED waste heat with an overall efficiency of 1%. We present an application of the active cooling powered by the harvested waste heat. The compact flat shape of the thin film thermoelectric generators allows an instant upgrade of the existing LED-based luminaries available on the market.

Introduction

The high luminous efficacy of more than 100 lm/W of the recent white high-power light emitting diodes (LEDs) outperforms significantly those of the conventional light sources such as incandescent light bulbs (16 lm/W) and compact fluorescent tubes (60 lm/W). However, the power conversion efficiency (PCE) of the white high-power LEDs is approximately 40% which means that still 60% of the input electrical power is converted into heat and lost. The waste heat produced by the incandescent, fluorescent or high-intense discharge light sources is predominantly dissipated by the heat radiation and convection into ambient space, giving no possibility for the waste heat recuperation. In contrast, the waste heat produced by high-power LED light sources is primarily transported by the thermal conduction into an appropriate heat sink which dissipates further the accumulated heat into ambient space. Hence, the current challenge is an efficient harvesting of the available waste heat of high-power LED light sources. The lighting is the second largest "consumer" of the residential electricity as reported by the U.S. Energy Information Administration (EIA). In 2014, the residential lighting consumption in U.S. was approximately 150 billion kWh which is about 15% of the total residential electricity consumption [1]. If we assume even a low 1% efficiency of the waste heat recovery, savings of more than 1 billion kWh in residential sector are possible, not counting the savings in the commercial sector. A relatively high conversion efficiency of the conventional heat engines based on the compression/expansion cycles is not applicable for the conversion of small heat fluxes of several W/cm^2 delivered by a single high-power LED light source. Quite the opposite, the conversion efficiency of the conventional heat engines at this low power level is even smaller than that of the thermoelectric generators [2]. Moreover, a potential high-power LED waste heat converter has to fulfill a number of stringent operation conditions. In particular, the form-factor of the waste heat converter has to be as small as possible in order to fit into the contemporary LED luminaries without any need for a substantial re-design. The waste heat convertor has to be free of any moving parts, operating silently, and its life time has to be at least comparable to that of the high-power LED itself. A thermoelectric generator (TEG) based on the thin film technology undoubtedly fulfills all these strict selection criteria [3]. Therefore, the current major drawback of thermoelectrics, the low heat-to-power conversion efficiency, can be overcome by integration of thin film thermoelectric generators directly into the high-power LED chips. Currently, the TEGs are an issue in automotive industry for the waste heat recovery from the exhaust systems [4,5].

In this paper, we present a thermal management setup suitable for the waste heat recovery of a single white high-power LED with the overall waste heat-to-power efficiency of about 1%. The latest

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thin film thermoelectric generators support the high heat fluxes above 10 W/cm^2 that compare well with those available from the high-power LED single chips. We demonstrate that the recovered 100 mW electrical power can be used to drive an additional active cooling which increases the luminous flux of the high-power LED due to lowering the LED junction temperature. Another applications can utilize the recovered electrical power for charging the emergency light batteries or other similar off-network devices in close proximity.

The thermoelectric design

The working principle of TEG is based on Seebeck effect [6,7]. In particular, the temperature difference between two electrically and thermally conducting materials that are in contact provides the thermoelectric voltage $V = \alpha\Delta T$, where α is the Seebeck coefficient. Hence, the heat transported through such a thermocouple generates the electrical current. Because of a low generated voltage of a single thermocouple at a given temperature gradient between the two materials, a large number of thermocouple pairs composed of n- and p-type semiconductors are sandwiched between two electrically isolated and good thermally conducting plates in TEGs. being electrically wired in series. In this way, a usable output voltage can be generated. The TEG conversion efficiency is primarily given by the available temperature difference and the material properties characterized by a dimensionless parameter $zT = \alpha^2 T/\rho\kappa$, also called thermoelectric figure of merit [8,9]. The ρ and κ are the electrical resistivity and thermal conductivity of a given material at temperature T, respectively. It is obvious that a good material for TEG with high zT requires a high electrical conductivity and a low thermal conductivity at the same time [10]. In the last decade a number of new promising materials with giant Seebeck coefficients were published including MnO_2 [11–13], $SrTiO_3$ [14,15], SnSe [16] and carbon-based [17,18] materials. The coming generation of high efficiency TEGs based on this new class of materials holds a promise for even more effective utilization in the LED waste heat recovery. The commercially available TEG materials suitable for the low temperature power generation, such as Bi_2Te_3, have $zT \approx 1$. The best materials developed up to now have the zT values close to two [10,19–21]. The traditional bulk Bi_2Te_3 devices are suitable for the low heat flux applications up to approximately 10 W/cm^2. In the last decade, the TEGs based on micro-structured Bi_2Te_3 thin films capable of supporting high heat fluxes above 100 W/cm^2 were developed [3]. These thin film TEGs are especially suitable for the integration with high-power LEDs due to their small size and low thermal resistance able to efficiently conduct the heat generated at the LED junction. The Table 1 compiles the generated power densities [22] per area P/A and volume P/V of currently commercially available thin film TEGs along with their thermal resistances θ_{TEG}.

The parameters in Table 1 were calculated based on the data available from the datasheets of manufacturers. The maximum temperature of the hot side of thin films TEGs should not exceed 150 °C. The thin film TEG module HV56 provides the highest generated power density per area and volume of all TEGs at the temperature difference of 10 K. The lowest thermal resistance θ_{TEG} = 13.1 K/W of all evaluated TEGs also favors the utilization of HV56 module for the waste energy harvesting of high-power LEDs. The incorporation of thin film TEGs into the thermal dissipation system of high-power LEDs requires individual optimization of the heat flow through the system [23–25]. In particular, the thermal resistance of the TEG has to be matched to the thermal resistance of the heat sink system [26]. The power P generated by the waste heat Q at the temperature difference ΔT_{TEG} across the TEG module can be written as [7].

$$P = \eta Q \approx \eta_1 \Delta T_{TEG} Q. \tag{1}$$

Here, η is the absolute conversion efficiency which can be approximated by a linear function of ΔT_{TEG} for low temperature differences. The quantity η_1 is given by the material properties [7]. In the following analysis, we neglect the Peltier and Joule heat terms [26,27] which have comparably small contributions compared to the conduction term of the waste heat Q. If we assume that the temperature difference ΔT_{TEG} can be written as $\Delta T_{TEG} = \theta_{TEG} Q$, the Eq. (1) can be re-arranged as

$$P \approx \eta_1 \theta_{TEG} Q^2 \tag{2}$$

which means that for a given waste heat Q the generated power P by the TEG module is directly proportional to its thermal resistance θ_{TEG}. On the other hand, the thermal resistance of the TEG module directly affects the temperature of the LED junction which should be kept as low as possible. Despite high allowable maximum temperatures of the contemporary high-power LEDs exceeding 150 °C, a long-life reliable operation is typically guaranteed for the LED junction temperatures of 100–110 °C at maximum. Moreover, operation of high-power LEDs above the optimum junction temperatures reduces their luminous efficacy. The LED junction temperature T_j can be calculated as [28,29]

$$T_j = T_a + \theta_{Hx} Q \tag{3}$$

$$\theta_{Hx} = \theta_{j-sp} + \theta_{TIM} + \theta_{TEG} + \theta_{HS} \tag{4}$$

where θ_{Hx} is the thermal resistance of the whole heat exchanger system and T_a is the ambient temperature. The quantity θ_{j-sp} is the thermal resistance from LED junction to solder point, θ_{TIM} is the total thermal resistance of all interfaces, and θ_{HS} is the thermal resistance of the heat sink used to dissipate the waste heat into ambient air.

In the following we will optimize the thermal design of the high-power LED from Cree, model XLamp MT-G EasyWhite. This LED is appropriate for applications that require high luminous flux from a well localized small spot. It is typically used for general indoor illumination as well as to retrofit the conventional light bulbs. The thermal resistance θ_{j-sp} of this high-power LED has a low effective value of 1.5 K/W (LED datasheet). The typical and maximum operation currents are I_{LED} = 1.1 A (at forward voltage U_F = 5.6 V DC) and I_{LED} = 4 A (at forward voltage U_F = 6.7 V DC), respectively. We restrict the maximum operating LED current to 3 A in order to preserve a long lifetime of final device. The generated waste heat is estimated as $Q = I_{LED} \cdot U_F \cdot (1 - \eta_{PCE})$ where $\eta_{PCE} \approx 0.4$ is the electrical power-to-radiant flux conversion efficiency of the high-power LED used. Using the Eqs. (2) and (3) we can optimize the number of utilized TEG modules appropriate for a safe LED operation. In the following we assume the largest affordable heat sink with the thermal resistance θ_{HS} = 0.35 K/W at ambient room temperature of 25 °C. A standard solder with the thermal conductivity of 50 W/m. K [30] gives the thermal resistance of approximately 0.31 K/W for a single 100 μm thin layer. If we consider two thermal interfaces for each TEG module, the total thermal resistance θ_{TIM} of all interfaces is $\theta_{TIM} = 2 * \frac{0.31}{n} (K/W)$ where n is the number of the TEG mod-

Table 1
The generated power densities at ΔT = 10 K and the thermal resistances of three available thin film TEG modules.

Model (manufacturer)	P/A (μW/mm^2)	P/V (μW/mm^3)	θ_{TEG} (K/W)
HV56 (LairdTech)	145	255	13.1
Thermo Life (Thermogen Technologies)	2	1.4	42.8
MPG-D655 (Micropelt)	78	71	22