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A design of a PhC-enhanced LED for electroluminescence cooling

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ABSTRACT

It is known that the wall-plug efficiency (WPE) of a light-emitting diode (LED) can exceed unity and that electroluminescence cooling (ELC) happens in this scenario. However, it is difficult to observe the associated temperature drop due to the relatively small cooling power and the overwhelming heat flux from the ambient. In this work, we design a photonic crystal (PhC) enhanced LED which has smaller surface area as well as thermal mass compared with an encapsulated LED. We also present thermal models to evaluate the temperature drop of the LED in air and vacuum.

Keywords: electroluminescent cooling, optical refrigeration, light-emitting diode, thermal model

1. A BRIEF REVIEW OF ULTRA-EFFICIENT LEDS

1.1 Previous Work on Ultra-efficient LEDs

A forward biased light-emitting diode (LED) consumes low-entropy electrical power and pumps heat into the incoherent photon field if the LED operates at voltages below the photon energy ($qV < \hbar\omega$).[1–3] In this scenario, the wall-plug efficiency (WPE, η_{WPE}) of the LED is over 100% and net cooling might be observed. The phenomenon is called electroluminescent cooling (ELC) and has been studied for over half a century. In 1957, Tauc pointed out that carrier diffusion in semiconductor diodes is assisted by lattice heat.[4] After Tauc's work, people built various theoretical models to study the ELC effect and the thermodynamic limitations of the energy conversion from lattice heat to optical power.[5–9] At the device level, Heikkila *et al.* reported a detailed model of ultra-efficient LEDs concerning with carrier transport, recombination and photon extraction processes.[3] According to their numerical results, a GaAs LED might generate 1 W/cm^2 of cooling power. The thermo-electrical pumping effects in LEDs of various wavelength were also observed and reported by experimentalists.[10–13] The first observation of $\eta_{WPE} > 1$ is reported in 2012 when Santhanam *et al.* used lock-in measurement tools to demonstrate an infrared GaInAsSb/GaSb LED with η_{WPE} over 200% at 135 °C.[1] In 2013, higher-than-unity η_{WPE} was achieved in mid-infrared LEDs at room temperature.[14] All these ultra-efficient LEDs operated at extremely low bias ($qV \ll kT$), and their output power densities were merely several hundreds nW/cm^2, which is not enough for direct observation of temperature drop. In order to enhance the output power, Gray *et al.* optimized the doping concentration and the active region thickness of a GaInAsSb/GaSb LED and the output power of the redesigned LED at $\eta_{WPE} = 1$ was enhanced by a factor of 621 at room temperature.[15] However, considerably higher output power is still desired to overcome the convection heat flux which is approximately 2 mW/cm^2 for a 1 K temperature difference in the air.[16] To the best of our knowledge, a direct measurement of the ELC temperature drop has not been reported.

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1.2 Definitions of Efficiency

An LED operates under forward bias and diffusion currents dominate the transport. Carriers are injected into the active region (AR) where each of the electron-hole pair has probability to recombine. There are three main recombination channels including Shockley-Read-Hall (SRH) recombination, bimolecular recombination and Auger recombination and their recombination rates, r_{SRH},r_{bi} and r_{Aug} scale with carrier concentrations as N, N^2 and N^3, respectively. Among the three main recombination channels, only the bimolecular recombination is radiative and contributes to the output power. We define the intrinsic quantum efficiency (IQE, η_{IQE}) as

$$\eta_{IQE} = \frac{r_{bi}}{r_{SRH} + r_{bi} + r_{Aug}} \approx \frac{BN^2}{AN + BN^2 + CN^3} \tag{1}$$

where A, B, and C are the recombination coefficients of SRH, bimolecular and Auger recombination, respectively. n is the majority carrier concentration.

EQE is the ratio of the escaped photons to the injected electron-hole pairs, and thus is the product of IQE and extraction efficiency as

$$\eta_{EQE} = \eta_{IQE} C_{ex} \tag{2}$$

where C_{ex} is the extraction efficiency.

WPE is the energy conversion efficiency. Since each electron-hole pair gains qV energy from the battery and each escaped photon on average has $\hbar\omega$ energy, we have

$$\eta_{WPE} = \frac{\hbar\omega}{qV} \eta_{EQE} \tag{3}$$

Here we can define $\eta_{elec} = \frac{\hbar\omega}{qV}$ as the electrical efficiency, which describes the energy conversion of a electron-hole pair through radiative recombination. It is also convenient to define a cooling efficiency as

$$\eta_c = \eta_{WPE} - 1 \tag{4}$$

Obviously, a cooling LED has $\eta_{WPE} > 1$ and $\eta_c > 0$. Since η_{EQE} has an intrinsic upper bound of 1, $\eta_{elec} < 1$ is necessary for LED operation.

1.3 Extraction Approaches

In a planar LED die, the emitted photons suffer from total internal reflection. A common and effective extraction approach to package the LED die with an index-matched hemispherical lens. The schematic plot is present in Fig. 1 where the black and blue blocks indicate the LED die and the packaging, respectively. The die is usually significantly smaller than the lens and is located at the center of the hemisphere. In this scheme, the emitted ray (red arrow) is approximately perpendicular to the hemisphere/air interface (black dash line) and thus the extraction is improved.

The state-of-the-art LEDs with proper packaging can easily have $C_{ex} > 90\%$.[13] The packing processes are also mature and widely applied in commercial LEDs. However, as we will discuss in 2, due to the large surface area and thermal mass of an encapsulated LED, we need eliminate the package to maximize the ELC temperature drop.

Another method to enhance the extraction is through emission surface roughening, which randomizes trajectory of the rays. As in Fig. 2, the blue area indicates the LED die and the red arrow is one ray trajectory. Here the top surface is the emission surface the the bottom is assumed to be reflective. If the rough feature is on the same order of the wavelength, the reflection at the top is diffusive and thus each reflected ray has certain probability to be redirected into the extraction cone after several bounces as present.

In thin-film LED technology, the epitaxial layer is usually separated from its absorbing substrate and bonded onto a metal reflector, and then the emission surface is textured.[17–20] In 1993, Schnitzer et. al. investigated the EQEs of epi-lift-off thin-film GaAs/AlGaAs LEDs with dielectric-coated Au reflectors.[19] It turned out that with a textured emission surface the EQE can be boost to 30% while the EQE is 9% for a planar surface.

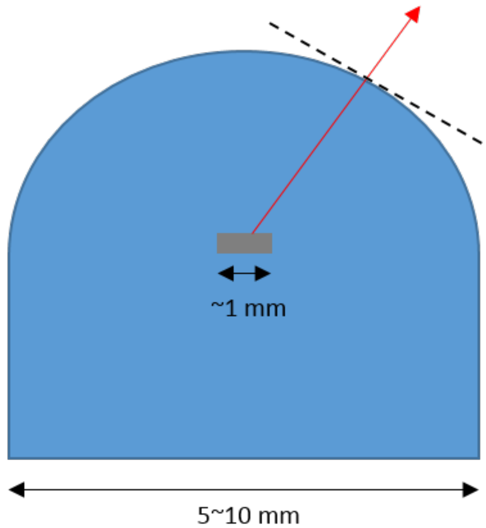


Figure 1. An encapsulated LED.

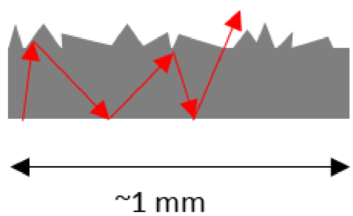


Figure 2. An LED with rough emission surface.

Rooman et. al. studied the GaInP/AlGaInP LEDs and compared the effect of using different materials between the bonded metal mirror and the epitaxial layers.[18] They concluded that the silver-loaded epoxy outperforms benzocyclobutene for doubling the achievable current while it keeps the EQE above 50%. With a very similar flip-chip and metal bonding processes in nitride material systems,[21] Haerle et. al. achieved $C_{ex} = 75\%$ for unencapsulated III-N LEDs.[20] Moreover, people also apply the surface texturing technology for volumetric LEDs with the dies usually shaped into special geometries and encapsulated, with the EQE exceeding 90%.[13,22]

Another method to extract photons in LEDs is to etch photonic crystal (PhC) structure onto the emission surface. (Fig. 3(a)) The PhC pattern introduces periodic dielectric perturbation, and the structure can be characterized by a reciprocal lattice $\{G\}$ as

$$\epsilon(r) = \sum_G \epsilon_G \exp(iG \cdot r) \tag{5}$$

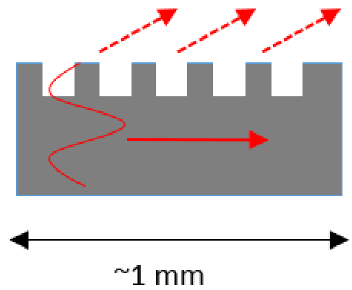
The modes propagating in the PhC are therefore harmonically coupled as Bloch modes

$$E(r) = \sum_G E_G \exp\left(i(k_{//} + G) \cdot r\right) \tag{6}$$

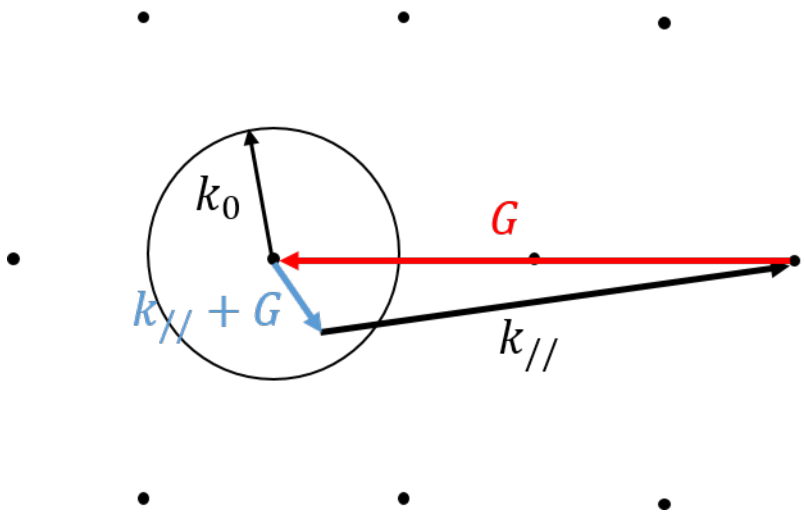
where $k_{//}$ in the the in-plane wavevector. When a harmonic satisfies the condition:

$$|k_{//} + G| < k_0 \tag{7}$$

where k_0 is the wavevector in air, it is in the extraction cone and the associated Bloch mode radiates energy into air.[23,24] (Fig. 3(b))



(a) PhC extraction.



(b) Ewald construction of the extraction.

Figure 3. Extraction process in a PhC LED.

For a leaky harmonic, the in-plane wavevector is complex and thus the energy $I(x)$ decays exponentially as the mode propagates in the x direction as

$$I(x) = I_0 \exp(-\alpha_{ext} x) \tag{8}$$

where α is defined as the extraction coefficient. Usually, the extraction process competes against the absorption process such as free carrier absorption, metal absorption and band edge absorption. The extraction efficiency is determined as

$$C_{ex} = \frac{\alpha_{ext}}{\alpha_{ext} + \alpha_{abs}} \tag{9}$$

where α_{abs} is the absorption efficiency.

The PhC enhanced LEDs have been investigated for over two decades and are proved to be highly efficient. In 1997, Fan et al. investigated the spontaneous emission from a dipole source in a PhC slab, and the calculation showed that nearly all the light can be extracted.[25] Erchak et al. fabricated optically pumped PhC LEDs with the PhC parts not penetrating into the active regions, and found a sixfold photoluminescence intensity enhancement.[26] Wierer et al. investigated GaN LEDs with a similar PhC structure, and they claimed the LEDs could have an extraction efficiency over 70%.[27]

Table 1 summarizes the highest measured C_{ex} of the mentioned extraction methods. The encapsulated LEDs have the best performance but are not considered as candidates for ELC due to its large surface areas. (See 2.) The unencapsulated LEDs have similar C_{ex}. However, the PhC patterned LEDs are more straightforward

extraction method	C_{ex}	reference
encapsulated LED	$> 90\%$	[13]
unencapsulated: textured thin film LED	75%	[20]
unencapsulated: PhC patterned LED	$> 70\%$	[27]

Table 1. Summary of the highest measured C_{ex} of the mentioned extraction methods.

to model while the models for the distribution of photons in the surface roughened LEDs are still controversial.[23,24,28] Also, there are both theoretical and experimental work showing that PhC patterned unencapsulated LEDs have higher extraction coefficient than surface roughened LEDs.[24,27] Therefore, in this thesis, we will choose PhC patterned LED when it comes to unencapsulated devices.

1.4 Optical Refrigeration

It is also worthwhile to compare optical refrigeration and electroluminescent cooling here. Optical refrigeration, or laser cooling, refers to cooling of macroscopic materials by anti-Stoke emission and was first theoretically investigated by Pringsheim in 1929.[29] For solid-state materials, the phenomenon was first experimentally demonstrated in rare-earth metal doped glasses in 1995.[30] In 2010, Seletskiy *et al.*, reported laser cooling of ytterbium doped glasses to 110 K from room temperature.[31] Semiconductors are also attractive and promising materials for optical refrigeration.[32–35] One of the most intensively studied semiconductor devices for optical refrigeration are GaAs based quantum wells, whose EQE can be as high as 99.5%.[36,37] However, due to strong parasitic absorption, net cooling has not been achieved in III-V quantum wells. In 2013, Zhang *et al.* reported the first laser cooling of 40 K in in CdS nanowires, which have strong coupling of exitons and longitudinal optical phonons (LOP), high EQEs, and weak parasitic absorption.[38]

The cooling processes of optical refrigeration and electroluminescent cooling are only different by pumping sources which are optical and electrical power. Similar to Section 1.2, we can define associated efficiency for optical refrigeration processes. Note the electrical efficiency is

$$\eta_{elec} = \frac{\hbar\omega_f}{\hbar\omega_i} \tag{10}$$

where $\hbar\omega_f$ and $\hbar\omega_i$ are the averaged photon energy of the emission and pump light, respectively. The cooling efficiency is defined as[33]

$$\eta_c = \eta_{EQE}\eta_{abs}\eta_{elec} - 1 \tag{11}$$

Here η_{abs} is the absorption efficiency, which describes the relative strength of band edge absorption and parasitic absorption.

The anti-Stoke emission is assisted by LOPs and thus the difference of $\hbar\omega_f$ and $\hbar\omega_i$ is on the order of kT, and η_{elec} is usually smaller than 105%.[31,38] Therefore, η_{abs} and η_{EQE} have to be closed to unity to guarantee an $\eta_c > 0$. The requirement for EQE can be lower for electroluminescent cooling because $\eta_{elec} = \frac{\hbar\omega}{qV}$ can be arbitrarily high by applying low voltage. However, electroluminescent cooling processes usually have more severe parasitic loss due to the metal contact and the associated high-doped contact layers.

2. THERMAL MODELS

2.1 Ultra-efficient LEDs with Low Output Power

We first consider the fact that the output power of an ultra-efficient LED is naturally low. According to Eq. 3, it is necessary to have

$$qV < \hbar\omega\eta_{EQE} \tag{12}$$

to make $\eta_{WPE} > 1$. The existence of the upper bound on the applied voltage limits the output power as well as the cooling power.

The cooling power can be expressed as

$$P_{cool} = IV(\eta_{WPE} - 1) \approx I_0 V \exp\frac{qV}{kT}\left(\frac{\hbar\omega}{qV}\eta_{EQE} - 1\right) \tag{13}$$

where I_0 is the saturation current of the device. From Eq .1,2, we see that the EQE is a function of carrier density and hence applied voltage. For the sake of a rough estimation, we assume η_{EQE} does not change much near the upper bound. It can be conveniently derived that the maximum cooling power is obtained at

$$V = \hbar\omega\eta_{EQE} - kT \tag{14}$$

which is closed to the upper bond. Therefore, the output power at $\eta_{WPE} = 1$ and the maximum cooling power both increase exponentially with η_{EQE} since the upper bound of V is proportional to EQE. For instance, Santhanam *et al.*'s LED has an EQE of approximately 10^{-4} in the regime that $\eta_{WPE} > 1$, and the applied voltage is approximately 70 μV.[1] Therefore, the cooling power is as low as nW/cm^2.

2.2 Cooling in Air

An LED with over-than-unity WPE generates cooling power which competes against the heat flux from the ambient. In air, the heat flux is mainly from the air convection. According to Newton's law of cooling we have

$$C\frac{d(\Delta T)}{dt} = -P_{cool}A_{em} - h_{air}A\Delta T \tag{15}$$

or

$$\Delta T = -\frac{P_{cool}A_{em}}{h_{air}A}\left[\exp\left(-\frac{t}{\tau}\right) - 1\right] \tag{16}$$

and

$$\tau = \frac{C}{h_{air}A} \tag{17}$$

where ΔT is the temperature difference of the LED and the ambient. The air convective heat transfer coefficient $h_{air} \approx 2 \times 10^{-3} W/(cm^2 \cdot K)$. P_{cool} and A_{em} are the cooling power and the emission area of the die respectively. C and A are the thermal capacity and the total surface area of the LED including packing.

First we consider an encapsulated LED. The dimensions of the device and the LED die are assumed to be $0.5 \times 0.5 \times 0.5\ cm^3$ and $0.1 \times 0.1\ cm^2$, respectively. We have $A = 1.5\ cm^2$, $A_{em} = 0.01\ cm^2$. According to Eq. 16, if we observe 1 K temperature drop, at least we have

$$P_{cool} = \frac{h_{air}A\Delta T}{A_{em}} \approx 0.3\ W/cm^2 \tag{18}$$

According to Heikkila *et al.*'s model,[3] this would require that both IQE and C_{ex} are approximately unity.

In contrast, if we use an unencapsulated LED, $A \approx 2A_{em}$, and

$$P_{cool} \approx 4\ mW/cm^2 \tag{19}$$

which is a hundred smaller than the encapsulated case. Due to the limited cooling power and the requirement of reducing the surface area, unencapsulated LEDs are preferred for direct observation of ELC.

We have designed an unencapsulated PhC-enhanced infrared LED which generates cooling power of $P_{cool} \approx 300\ \mu/cm^2$. According to Eq. 16, the $\Delta T - t$ plot is present in Fig. 4. The temperature drop of 0.1 K can be measured by a thermocouple.

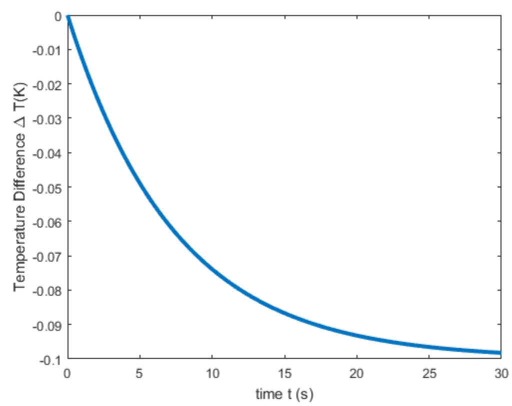


Figure 4. Cooling process in air.

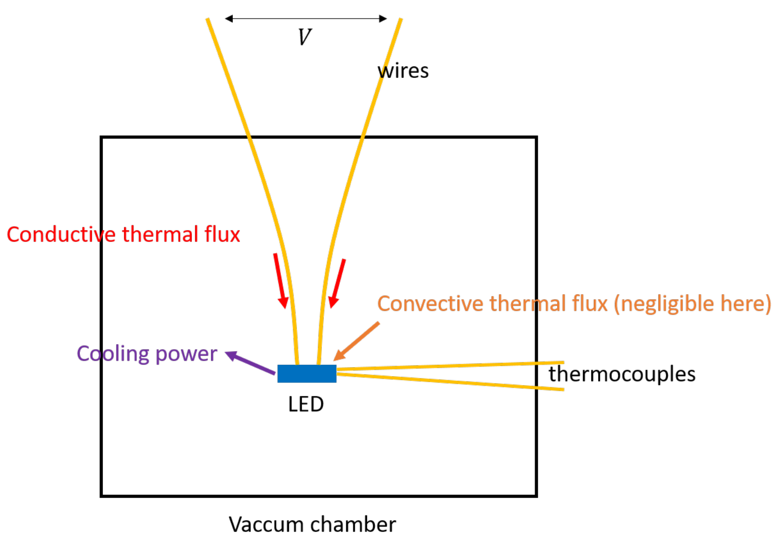


Figure 5. Proposed setup to measure cooling in vacuum. Thermal flux and cooling power are indicated.

	sign	value	comment
LED density	ρ_d	$4.8\ g/cm^3$	
LED length	l_d	$0.1\ cm$	
LED thickness	t_d	$200\ \mu m$	handle included
LED specific heat	c_d	$0.31\ J/(g\ K)$	
LED thermal conductivity	k_d	$0.68\ W/(cm^2\ K)$	
Air convection coefficient	h_{air}	$2 \times 10^{-3}\ W/(cm^2\ K)$	[16]
Wire length	l_w	$0.5\ m$	
Wire radius	r	$100\ \mu m$	
Wire specific heat	c_w	$0.38\ J/(g\ K)$	
Wire density	ρ_m	$8.9\ g/cm^3$	
Wire electrical resistivity	ρ_e	$10^{-5}\ \Omega \cdot cm$	
Wire thermal conductivity	k_w	$0.48\ W/(cm^2\ K)$	
Cooling power	P_{cool}	$300\ \mu/cm^2$	maximum cooling
LED current density	I_d	$0.01\ A/cm^2$	
Wire current density	I_w	$0.3\ A/cm^2$	$I_w = I_d \frac{l_d^2}{\pi r^2}$

Table 2. Parameters in our thermal models.

2.3 Cooling in Vacuum

A more dramatic temperature drop should be observed if we put the LED into a vacuum chamber to eliminate the air convection. We propose to use the electrical wires as mechanical support of the LED. In this scenario, the cooling has to compete against the heat flux from the wire. The heat sources are the Joule heat generated and the chamber which is thermalized with the ambient. (See Fig. 5) The parameters we will use are listed in Table 2.

The temperature distribution $T(x,t)$ along the wire satisfies

$$\rho_m c_w \frac{\partial T}{\partial t} = I_w^2 \rho_e - \frac{k}{l_w} \frac{\partial^2 T}{\partial x^2} \tag{20}$$

At $x = 0$ and $x = l_w$ the wire is connected with the chamber and the LED, respectively. The boundary conditions are thus

$$T|_{x=0} = T_0 \tag{21}$$

and

$$\pi r^2 k_w \left.\frac{\partial T}{\partial x}\right|_{x=l_w} = -\frac{1}{2} P_{cool} l_d^2 \tag{22}$$

where $T_0 = 300\ K$ is the ambient temperature. The prefactor $\frac{1}{2}$ exists because two wires are symmetrically connected to the LED. Note that in Eq. 22, we assume the thermalization of the LED is much faster than the wires because the thermal conductance of the wires K_w is much smaller than that of the LED K_d since

$$\frac{K_d}{K_w} = \frac{k_d}{k_w} \frac{l_d^2}{\pi r^2} \frac{l_w}{t_d} \approx 10^5 \tag{23}$$

In Fig. 6 we present the cooling process in vacuum. The temperature drop at the LED end of the wire is $0.1\ K$ and $0.2\ K$ after 10 min and 30 min, respectively. For the steady state, the temperature drop is approximately $0.5\ K$.

3. CONCLUSION

In this report, we first review basic concepts and definitions of ELC. We point out the cooling power of an ELC LED is low and unencapsulated structures are required for direction observation of temperature drop. The cooling processes both in air and in vacuum are simulated based on our designs.

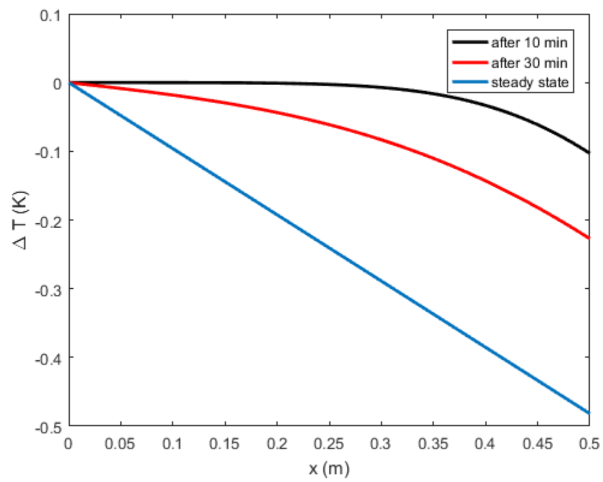


Figure 6. Cooling process in vacuum.

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