Investigation of temperature dependence of radiation from semiconductor lasers and light emitting diodes

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Abstract. The investigation of temperature dependences of the radiation from red semiconductor laser diodes and light emitting diodes (LEDs) made on the basis of AlGaInP quadruple solid solution has been carried out. Despite the fact that the basic reasons for the change in the wavelength of laser and LEDs radiation when the temperature changes are considered to be known, however, the details of this effect are not well understood. The research shows experimentally how the radiation wavelength changes with temperature changes in the range from -20°C to 40°C for both a semiconductor laser and a LED. It was found that the rate of change in the radiation wavelength of the devices under study differs when the temperature changes. Two linear sections can be distinguished on the laser diode dependence of the wavelength on temperature \( \lambda (T) \), while the LED has one section on the dependence \( \lambda (T) \). The paper provides an explanation of the observed patterns based on the analysis of the possible influence of various factors. The study is relevant due to the fact that the devices under study are operated in the Arctic region, both at low and high temperatures, and there is insufficient information about the effect of temperature on the radiation characteristics of the studied devices.

1. Introduction
Currently, LEDs, semiconductor laser modules are widely used in various equipment, and these devices can work not only in closed rooms with a fairly stable temperature, but also in open space, both at low and high (compared to room) temperature.

It is noted that laser diodes lack a fixed value of the generation frequency, since this value is determined by the operating pump current and temperature [1], [2], [3], [4].

In [1], it was noted that in the case of semiconductor lasers, frequency tuning can be carried out by changing the temperature of the laser diode. From our point of view, despite the fact that the basic reasons for changing the wavelength of the laser radiation with a change in temperature are considered to be known, however, the details of this effect are not well understood. We previously showed that exciton energy levels can influence the temperature dependence of the semiconductor laser radiation wavelength [3], [4]. In view of the foregoing, in our opinion, further studies are required to clarify the details of the temperature effect on the radiation wavelength of a semiconductor laser and a LED operating in the visible range.

2. Main part
The temperature effect on the spectral characteristics of the radiation of the following objects was studied: a LED emitting in the wavelength range (625-640) nm (at a temperature of \( T = 293 \) K and
current strength of I = 30 mA); commercially available TXL-03 brand semiconductor laser diode emitting at a wavelength of 650 nm (at a temperature T = 293 K and a current strength of 20 mA). The objects under study are made on the basis of AlGaInP quadruple solid solution (QSS).

The temperature of the objects ranged from 259 K to 315 K. The radiation spectra of the objects were measured using an S150 spectrometer with the installed Toshiba TSD1304AP detector sensitive in the wavelength range (200–1100) nm.

Fig. 1 shows the radiation spectra of a semiconductor laser diode at various temperatures (indicated in the figure field). The ordinate axis shows the radiation intensity (relative units); the abscissa axis shows the wavelength λ.

![Figure 1. Temperature effect on the wavelength corresponding to the maximum radiation of a semiconductor laser diode (current strength I = 20 mA)](image)

In [1], the authors note that, at low injection currents, lasers, as a rule, generate several longitudinal modes. But as the pump current increases, one of the modes begins to prevail, and the width of the laser spectrum narrows. Figure 1 shows that the nature of the radiation spectrum of the investigated laser diode does not change with increasing temperature from 259 K to 315 K (one mode prevails), while the wavelength of the radiation maximum shifts by about 9 nm toward longer wavelengths.

In our opinion, it can be argued that, in the temperature range under study, a laser operation close to single-frequency one is implemented, despite the fact that the spectrum contains side modes that share the total radiation power with the main mode. As noted in [1], the question of what level of side modes is acceptable for the single-frequency operation remains open.

In connection with the experimental results presented in Fig. 1 two questions arise:
- What is the rate of change of the wavelength of the maximum laser radiation with increasing temperature?
- Is this rate the same in the temperature range studied?
In order to get answers to the questions posed, we constructed a wavelength dependence corresponding to the maximum of the laser radiation as a function of temperature (Fig. 2). Then the value $\frac{d\lambda}{dT}$ was graphically determined.

![Figure 2. Temperature dependence of wavelength of radiation from a semiconductor laser diode (I = 20 mA)](image)

Fig. 2 shows that on the dependence $\lambda (T)$, 2 linear sections can be distinguished: the first corresponds to the temperature range (258–285) K, and the second corresponds to the region (285–315) K. The transition from the first section to the second occurs at the temperature approximately equal to 285 K. The rate of change of the wavelength of the maximum laser radiation with increasing temperature $\frac{d\lambda}{dT}$ is 0.12 nm /K in the first section and 0.21 nm /K in the second section.

Note that in the literature [1] (with reference to [5]) a “typical value” of the rate of change of the wavelength of the radiation from a red laser diode emitting in the visible part of the spectrum is given, namely, (0.25-0.3) nm/K. Note that the value given in the literature is close to that one recorded in our experiment at temperatures above 285 K - 0.21 nm/K.

It is known that the wavelength of laser radiation is related to the value of band gap $E_g$ of the material of which the laser is made, by the following formula [6]:

$$E_g = \frac{hc}{\lambda}$$

(1)

where $h$ is the Planck constant, $c$ is the speed of light in vacuum.

The dependence of the band gap value $E_g$ of the laser diode material calculated according to formula (1) is shown in Fig. 3. It can be seen that the band gap value, determined by equation (1), decreases with increasing temperature.

On the dependence $E_g(T)$, as well as on the dependence $\lambda (T)$, two sections with different values $|\frac{dE_g}{dT}|$ are observed: $4.17 \cdot 10^{-4}$ eV/K in the temperature range (258–285) K and $5.71 \cdot 10^{-4}$ eV/K in the region (285–315) K.
The analysis performed by us earlier [7] showed that the QSS composition \((Al_xGa_{1-x})_yIn_{1-y}P\), having a band gap of \(E_g = 1.9\) eV at 300 K, corresponds to direct-band-gap structures, the lattice period being able to vary from 0.555 nm to 0.585 nm.

![Figure 3. Temperature dependence of the band gap value of a semiconductor laser diode (I = 20 mA)](image)

It is known that the wavelength of radiation from a semiconductor laser with a change in temperature is determined by both a change in the value of band gap of the laser material and the effect of temperature on the optical resonator length. The effect of temperature on the crystal band structure is believed to be due to two main factors: thermal lattice expansion, associated with the dependence of the carrier energy levels on the unit cell volume, and electron-phonon interaction [9], [10].

In [1] (with reference to [8]), dependence is given that indicates the effect of the optical resonator length on the radiation wavelength of a certain mode of the laser diode:

\[
\lambda_q(T) = \frac{2nL(T)}{q}
\]  

where \(n\) is the refractive index of the laser material; \(q\) is the mode number; \(L(T)\) is the optical resonator length.

It follows from formula (2) that the wavelength of any mode depends on the temperature of the laser diode, since the optical resonator length increases with increasing the temperature. This dependence will be the most noticeable for modes with low numbers. Based on formula (1), it can be argued that for the central mode (corresponding to the maximum radiation of the diode), the temperature dependence of the radiation wavelength will be the most noticeable.

As far as is known, the radiation spectrum of a LED is wider than that one of a laser diode, however, and a LED has a clearly defined maximum radiation. Figure 4 shows the emission band of the red LED at various temperatures in the range from 256 K to 294 K.

Figure 4 shows that the contour of the spectral band of the LED radiation does not change with increasing temperature from 256 K to room temperature 294 K. The maximum intensity of the absorption band shifts towards longer wavelengths as temperature increases, with its intensity decreasing (Fig. 4).
To determine the rate of change of the wavelength of the maximum LED radiation with temperature change, the temperature dependence of the maximum wavelength of the radiation band of a semiconductor LED was studied (Fig. 5).

It can be seen (Fig. 5), the dependence $\lambda (T)$ is linear for the LED. Unlike a semiconductor laser, there is one linear section for the LED on the dependence $\lambda (T)$. The rate of change of the wavelength of the LED maximum radiation with temperature change $\frac{d\lambda}{dT}$ is 0.16 nm / K.

![Figure 4. Characteristics of emission spectrum of the red LED (I = 20 mA) at various temperatures: 1 - 256 K; 2 - 262 K; 3 - 274 K; 4 - 288 K; 5 - 294 K.](image)

It can be assumed that the difference in the $\lambda (T)$ dependence between the laser diode and LED (presence of two sections with different values $\frac{d\lambda}{dT}$ for the laser and one section for the LED) is due to the presence of optical resonator in the laser diode, which, according to formula (2), can have an additional effect on a change in the radiation wavelength with temperature change. The total change in the radiation wavelength of both the laser diode and LED in the temperature range from 258 K to 310 K is approximately equal to 8.5 nm for the laser and 8.6 nm for the LED.

From the presented experimental results, it can be concluded that the effect of the optical resonator on the radiation wavelength of a single-frequency laser is ambiguous: on the one hand, there may be a change in magnitude $\frac{d\lambda}{dT}$ in different temperature ranges, but the total change in the wavelength of the maximum radiation in a specific temperature range (258 K ÷ 310 K) is actually the same as that one of the LED.
It is not unlikely that the difference in the \( \lambda(T) \) dependences observed for the laser and LED can be due to the different composition of the QSS \((Al_xGa_{1-x})_yIn_{1-y}P\). Note that for commercially available devices, the specific composition of the QSS is not indicated.

The value of the band gap of the LED material was calculated by the formula (1). Based on the calculations, the temperature dependence of the value of the semiconductor LED band gap was constructed (Fig. 6).

Figure 6 shows that the band gap value \( E_g \) decreases with increasing temperature. The value of \( \left| \frac{dE_g}{dT} \right| = 5 \times 10^{-4} \text{eV/K} \). Note that on the dependence \( E_g(T) \), as well as on the dependence \( \lambda(T) \) of the LED, there is only one linear section.

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**Figure 5.** Temperature dependence of wavelength of LED maximum radiation band \((I = 30 \text{ mA})\).

Earlier, we investigated the temperature dependences of the radiation wavelength of commercially available laser diodes of two grades in the temperature range \((50-290) \text{ K}\). It was shown that in the temperature range under study, either two or three linear sections with different value \( \frac{d\lambda}{dT} \) can be distinguished [3], [4].
Figure 6. Temperature dependence of band gap value of semiconductor LED material (I = 30 mA)

Based on the experimental results of this work, as well as on the results obtained by us earlier [6], it is possible, in our opinion, come to the following conclusion: the statement that the frequency tuning of semiconductor lasers can be carried out by changing the temperature of the laser diode is overly optimistic at this stage of the research.

3. Conclusion
In reality, each of the semiconductor lasers studied by us demonstrated “individual” features of the $\lambda(T)$ dependence. To explain the observed features, some arguments can be given.

Apparently, first of all, the effect of the AlGaInP quadruple solid solution composition on the $\lambda(T)$ dependence should be studied in detail. Then, we should study the effect of the optical resonator design features on the $\lambda(T)$ dependence. After carrying out this kind of research, one can hope that the wavelength of the laser diode radiation will become possible to tune in a controlled manner by changing the temperature.

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