PHYSICAL OPTICS

Conference materials
UDC 535.8
DOI: https://doi.org/10.18721/JPM.153.231

Reliability of 808 nm QCW laser diode arrays

E. M. Gafurov [1] ✉, E. V. Smirnov [1]

[1] FSUE "RFNC-VNIITF named after Academ. E.I. Zababakhin", Snezhinsk, Russia

✉ dep5@vniitf.ru

Abstract. The dependence of radiative characteristics of 808 nm QCW laser diode arrays (LDAs) on power supply modes and thermostabilization temperature was studied. The accelerated lifetime test method is suggested at 6% duty cycle exceeding the nominal value by a factor of 2.5 and at two emitter junction temperatures of 65.0ºC and 82.5ºC. Accumulated total LDA operation time in the accelerated mode was more than $7.0 \cdot 10^8$ pulses that allows predicting LDA operation time to be nearly $3.5 \cdot 10^{10}$ pulses in nominal power supply modes (i.e. more than 60 thousand hours or 7.0 years of continuous work at 100 Hz frequency).

Keywords: Reliability, QCW laser diode arrays, Arrhenius model, accelerated lifetime tests.

Citation: Gafurov E. M., Smirnov E. V., Reliability of 808 nm QCW laser diode arrays, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 15 (3.2) (2022) 167–171. DOI: https://doi.org/10.18721/JPM.153.231

Материалы конференции
УДК 535.8
DOI: https://doi.org/10.18721/JPM.153.231

Исследование ресурсных характеристик импульсно-периодических матриц лазерных диодов

Э. М. Гафуров [1] ✉, Е. В. Смирнов [1]

[1] ФГУП «РФЯЦ-ВНИИТФ им. академ. Е.И. Забабахина», г. Снежинск, Россия

✉ dep5@vniitf.ru

Аннотация. Проведены исследования зависимости излучательных характеристик импульсно-периодических матриц ЛД (МЛД) с длиной волны излучения 808 нм от режимов питания и температуры термостабилизации. Предложен метод ускоренных ресурсных испытаний при коэффициенте заполнения импульсов 6%, превышающем номинальное значение в 2.5 раза, а также при двух значениях температуры эмиттеров 65.0ºС и 82.5ºС. Накопленное суммарное время работы МЛД в ускоренном режиме составило более $7.0 \cdot 10^8$ импульсов, что позволяет прогнозировать длительность работы МЛД при номинальных режимах питания в течение около $3.5 \cdot 10^{10}$ импульсов (более 60 тысяч часов или 7.0 лет непрерывной работы при частоте следования импульсов 100 Гц).

Ключевые слова: надежность, матрицы лазерных диодов, модель Аррениуса, ускоренные ресурсные тесты

Ссылка при цитировании: Гафуров Э. М., Смирнов Е. В. Исследование ресурсных характеристик импульсно- периодических матриц лазерных диодов // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2022. Т. 15. № 3.2. С. 167–171. DOI: https://doi.org/10.18721/ JPM.153.231

Introduction

A large-scale research conducted by RFNC-VNIITF in the area of in-house development and production of diode-pumped solid-state laser (DPSSL) was focused on the design and production techniques of high-power QCW laser diode arrays (LDA) [1] with the following nominal characteristics: radiation power of 2.4 kW at 100 Hz frequency and 240 μs pulse width.

A major stage in production of LDAs and any other laser emitters (LEs) is to determine their reliability in the required operation modes. In turn, the rate of changing laser diode output characteristics which allows estimating reliability of products is affected by different degradation mechanisms of laser devices which can be determined only in the course of lifetime tests [2].

The topic of this research brings up the relevant issue related to long-term stability of LDA output characteristics and influence of different factors accelerating degradation process. On the one side, the lifetime of semiconductor laser emitters, including LDAs, depends on many factors, e.g. type of laser diodes (LDs) or laser diode bars (LDBs) used, LE design features, operation modes and operating conditions, that significantly complicates identification of degradation causes. On the other side, the lifetime of modern LEs exceeds tens of thousands of hours or 109 pulses thus making full-scale lifetime tests unfeasible under severe time constraints of up-to-date production.

Currently, the accelerated lifetime test method is commonly used to estimate LDA lifetime at the increased thermostabilization temperatures and/or optical radiation power, and this is the case of this study.

Accelerated lifetime test method

Degradation of injection lasers is caused by a number of mechanisms acting at current transmission. The prevailing mechanism depends on many factors such as growth technology of heteroepitaxial wafers, improvement of crystal structure, semiconductor laser chips production technology, design and mounting of LDs or LDBs on the heat sinks, and operating conditions.

Mechanisms causing failures of semiconductor devices, including semiconductor LEs, are mainly based on chemical and physical processes with temperature-depending rates defined by the Arrhenius equation [3]:

$$\upsilon = A\exp(-E_a / kT), \tag{1}$$

where A is the proportionality coefficient defining reaction intensity, i.e. the rate of interaction events per reaction; E_a is the activation energy defining the energy barrier for different states in a reaction, eV; k is the Boltzmann constant ($8.616\cdot10^{-5}$ eV/K); and T is the temperature in Kelvins.

Thus, to analyze and predict the degradation rate and, therefore, a semiconductor LE lifetime it is necessary to determine the activation energy representative for the specific degradation factor. In turn, the activation energy is determined by the analysis of several plots showing LDA optical radiation power vs. operating time at different power supply modes and thermostabilization temperatures.

As stated above, the increased temperature is one of the most common types of "loading", used when performing the accelerated lifetime tests. The Arrhenius model in its general form describes the influence of temperature, pumping current, and radiation power on lifetime. Based on the Arrhenius equation above it is possible to define acceleration coefficient, $\tau_{T,P}$, between lifetime under nominal operating conditions and that in the course of lifetime tests [4]:

$$\tau_{T,P} = \frac{\tau_1}{\tau_0} = \exp\left(\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right)\left(\frac{P}{P_0}\right)^{-n}\left(\frac{I}{I_0}\right)^{-m}, \tag{2}$$

Where T_0 and T_1 are the heat-sink temperatures under nominal operating conditions and in the course of accelerated testing, respectively; τ_0 and τ_1 are the LE lifetimes under nominal conditions and in the course of the accelerated testing, respectively. The activation energy, E_a, is usually reported by the manufacturer of semiconductor crystal or is determined from the results of accelerated lifetime tests. Values n and m are positive constants.

The EOL-criterion can be a 20% increase in initial LE pumping current, required to maintain constant output radiation power [5], or a relative decrease in output radiation power by 20% at LE direct current [6].

Experiment

Two samples of commercially available LDAs emitting at 795÷808 nm were studied. Chiller with heating function was used for LDA thermostabilization. Temperature of the array holder was controlled by TC-1388B calibrated thermoresistance.

Before studying LDA reliability it was necessary to determine those parameters of array power supply and external effects, whose change will have a direct impact on the degradation rate of the array radiative characteristics. For this purpose we examined the LDA power output and radiation wavelength vs. power supply parameters, i.e. pumping current amplitude, pulse frequency, and pulse width. The results of these studies, presented in Fig. 1, indicate that the change in LBD active region temperature and LDA radiation power depends on the integral value of duty cycle, whereas different combinations of pulse frequency and pulse widths do not lead to the deviation from the given linear dependence. This allows varying a limited set of parameters in the course of the accelerated lifetime tests, i.e. thermostabilization temperature of LDA heat-sink, duty cycle, and pumping current.

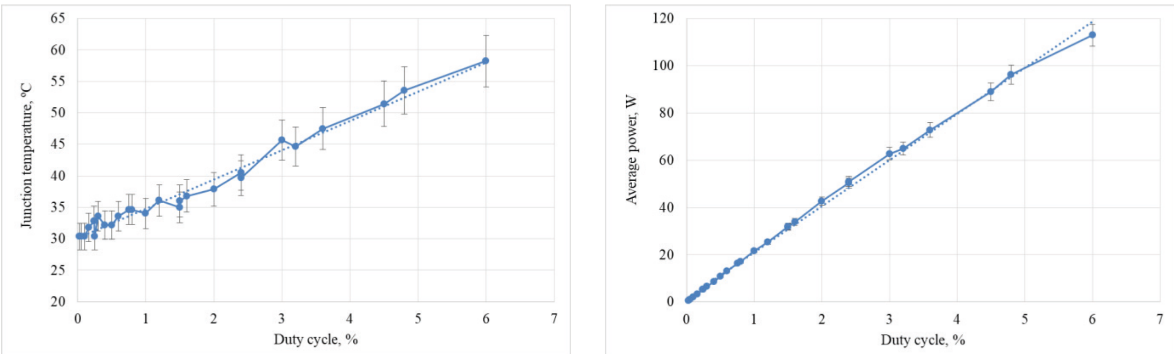

Fig. 1. Junction temperature and average radiation power vs. duty cycle

The temperatures of LDA holder were 25±0.5ºC and 45±0.5ºC for sample No. 1 and sample No. 2, respectively, in the absence of LDA power supply. According to the measurement results of LDA radiation wavelength, the temperatures of emitters (LDB active region) were 65.0±3.0ºC for sample No. 1 and 82.5±3.0ºC for sample No. 2 in LDA operation power supply modes at duty cycle of 6% and pumping current of 120A. For comparison, this temperature was 41.0±1.5ºC in nominal operation modes of LDA power supply at duty cycle of 2.4%, pumping current of 120A and array holder temperature of 25±0.5ºC, in the absence of power supply.

Fig. 2 presents LDA optical radiation power for sample No. 1 vs. shots in lifetime tests (discrete points) as well as the results of experimental data approximation by exponential function (solid line).

At the same time, the proportionality coefficient of approximation function exponent in Fig.2 is nothing else but the LDA degradation rate in the course of lifetime tests:

$$\frac{P(t)}{P_0} = \exp(-\upsilon * t), \tag{3}$$

where v is the LDA optical power degradation rate. This formula corresponds to the condition when the output power degradation rate slightly changes over time [6].

Then, the functional dependence of LDA degradation rate for two emitter temperatures was plotted as:

$$\ln(\upsilon) = \frac{E_a}{kt}. \tag{4}$$

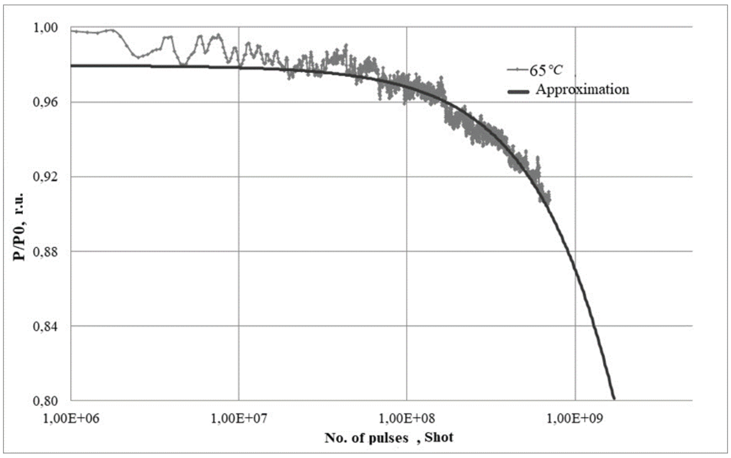

Fig. 2. The results of accelerated lifetime tests for LDA No. 1 at LDB junction temperature of 65 °C

According to Eq. 4, the slope of this plot is the desired activation energy. The LDA activation energy was $E_a = 0.72 \pm 0.07$eV. Next, using Eq. 2 and assuming power acceleration coefficient to be $n = 2$ according to [4, 8], we obtained the acceleration coefficient, $\tau_{T,P}$, and the expected LDA failure-free operation time in the course of the accelerated test. Finally, we calculated the LDA lifetime in the nominal operation mode.

In our case, the calculated acceleration coefficients between lifetime under nominal operating conditions and in the course of accelerated lifetime tests were 0.032 for sample No. 1 and 0.012 for sample No. 2. This allows estimating the failure-free operation time of LDAs made by RFNC-VNIITF under nominal operating conditions to be $3.5 \cdot 10^{10}$ pulses provided that the end of life in the course of the accelerated tests according to Fig. 2 will occur at $1.1 \cdot 10^9$ pulses.

Conclusion

The method for QCW LDA accelerated lifetime testing is suggested establishing the dependency of LDA failure-free operation time on thermostabilization temperature and power supply modes. The accelerated lifetime tests of two LDA samples made by RFNC-VNIITF were carried out. The tests were conducted at two LBD junction temperatures (65±3.0ºC for sample No. 1 and 82.5±3.0ºC for sample No. 2) and the duty cycle increased by 2.5 times. The activation energy of degradation processes for the LDAs under study was $E_a = 0.72 \pm 0.07$eV.

The collected results of accelerated lifetime tests allow predicting LDA failure-free operation time in the nominal operation modes to be no less than $3.5 \cdot 10^{10}$ pulses before EOL-criteria will be reached. LDA optical power degradation over time is likely caused by the gradual decrease in emitter quantum efficiency.

Further studies of LDA reliability will be proceeded to allow refining activation energies of degradation processes and power acceleration coefficient for the specific type of LDAs developed by RFNC-VNIITF.

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THE AUTHORS

GAFUROV Eldar M.
dep5@vniitf.ru
ORCID: 0000-0002-7405-4242

SMIRNOV Evgenii V.
dep5@vniitf.ru
ORCID: 0000-0002-0162-4689

Received 25.07.2022. Approved after reviewing 08.08.2022. Accepted 09.08.2022.