*Optica Applicata, Vol. XXXV, No. 3, 2005*

# Thermoreflectance study of temperature distribution on the semiconductor laser mirrors

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In the high-power semiconductor lasers, the surface of the mirror is the key element of the construction, which has the main impact on the reliability and degradation processes. In the case of lasers fabricated with the use of GaAs compounds the highest power emitted by the structure is limited by the catastrophic optical damage (COD) effect due to the increase of temperature on the air-semiconductor edge. The technique which enables examining the temperature distribution on the mirror surface is thermoreflectance. In this paper, we present the technique of temperature mapping on the mirror surface of the high power semiconductor lasers based on the thermoreflectance method.

Keywords: thermoreflectance, semiconductor laser, mirrors, temperature maps.

## 1. Introduction

Huge progress in the development of high-power semiconductor lasers in recent years introduced these structures into many applications such as solid-state laser pumping, thermal printing, soldering, and material processing [1]. Apart from enhancing basic parameters, such as efficiency and threshold current, important in applications of lasers are lifetime of the devices and highest emitted power. One of the main factors, which have the key impact on these parameters, is the temperature distribution on the mirror surface of the electrically pumped laser [2].

The temperature at the facet of a semiconductor laser has a critical role in device reliability and performance. The relevant failure process, known as catastrophic optical damage (COD), occurs at the facet where there is increased absorption of laser light due to surface states and subsequently, a higher operating temperature. This higher temperature results in the shrinking of the band-gap and thus a further increase in the local absorption. Such reinforcement can eventually lead to failure of a device. Thus, the local facet temperature is indicative of these processes and needs to be controlled to avoid failure. Nowadays many techniques are used to examine the temperature distribution on the mirror surface of the working semiconductor laser such as micro-Raman spectroscopy, cathode luminescence, photoluminescence, and reflectance modulation. From the above mentioned methods thermoreflectance, which is one of the reflectance modulation techniques, shows much greater speed of measurement as well as much better resolution and accuracy. In this study, a novel monitoring technique based on spatially resolved thermoreflectance (SRTR), which allows a complete mapping of temperature across the facet of any semiconductor laser device has been developed.

## 2. Thermoreflectance fundamentals

In general, optical modulation spectroscopy techniques measure the response of the optical constants of a sample to a periodic change of an applied perturbation [3]. The changes in real $\Delta\varepsilon_1$ and imaginary part $\Delta\varepsilon_2$ of dielectric function, induced by external modulation, result in relative change of reflectivity given by:

$$\frac{\Delta R}{R} = \alpha\Delta\varepsilon_1 + \beta\Delta\varepsilon_2 \tag{1}$$

where $\alpha$ and $\beta$ are Seraphin coefficients related to the unperturbed dielectric function [4].

Our special case is termed SRTR as a method to determine local absolute temperature of the semiconductor laser mirror, which relies on a periodic facet temperature modulation. In thermoreflectance, the modulation of temperature results in a change of dielectric function $\Delta\varepsilon$, which is induced by a shift of the band gap energy $E_g$ and by change of the broadening parameter $\Gamma$ [5],

$$\Delta\varepsilon = \frac{\partial\varepsilon}{\partial T}\Delta T = \frac{\partial\varepsilon}{\partial E_g}\frac{\mathrm{d}E_g}{\mathrm{d}T}\Delta T + \frac{\partial\varepsilon}{\partial\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}T}\Delta T. \tag{2}$$

Thus, the relative reflectance variation $\Delta R/R$ depends on $\Delta T$, the temperature variation with respect to the room temperature. This is thermoreflectance effect. The general expression $\Delta R/R$ might be expressed as a power series of $\Delta T$, but in most applications, the temperature variation is small enough for the higher order terms to be neglected. Thus, relative variation of reflectance $\Delta R/R$ is a linear function of temperature variation $\Delta T$:

$$\frac{\Delta R}{R} = \frac{1}{R}\frac{\partial R}{\partial T}\Delta T = C_{\mathrm{TR}}\Delta T \tag{3}$$

where $C_{\mathrm{TR}}$ is temperature coefficient dependent on experimental condition. In order to accurately determine the mirror surface temperature a calibration procedure is required.

Because temperature coefficient depends on experimental conditions, determination of accurate temperature requires calibration process. For each sample, the $C_{TR}$ coefficient was determined in a special experimental arrangement, by measuring the reflectance of the sample for a range of specific values of temperatures, and its value verified by micro-photoluminescence measurements performed in essentially the same experimental set up as thermoreflectance measurement.

## 3. Experimental setup

Thermoreflectance, like all modulation techniques, requires that a modulation factor and probe beam be applied to structure under examination. Supplying the laser diode with low frequency pulsed current (20–200 Hz) with filling factor 10–50% induced periodic changes of the laser mirror temperature. Under these conditions the laser was operating quasi-CW and was subjected to thermal effects associated with CW operation [6, 7].

The device was mounted on a high precision *x*-*y*-*z* piezo-translation stages used to align the laser mirror with respect to the probe beam, which was focused down on

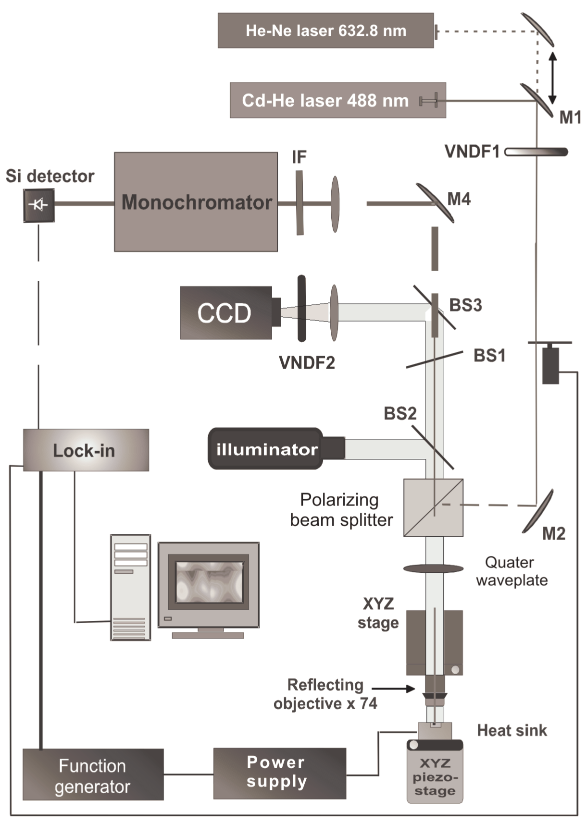


Fig. 1. Schematic diagram of experimental set-up for the laser mirror temperature measurement.

mirror surface. The size of the probe beam was diffraction limited, being as small as 1 μm. The use of piezoelectrically driven translating stages allowed detailed mapping of the temperature distribution over the laser facet (mapping range 300×300 μm). Temperature of the laser heat sink was stabilized with TEC supported by water-cooling. The linearly polarized CW He-Ne laser (632.8 nm) was used as a source of low power ($P < 0.5$ mW) probe beam. The beam from He-Ne laser was directed through polarizing beam splitter and quarter waveplate to commercial objective 74x (0.65NA) and then it was focused down on the semiconductor laser mirror. After reflection from the lasers surface, the probe beam went back the same way through the waveplate to polarizing beam splitter where it was splitted. The reflected light was collected by lens and focused on silicon detector. The light striking the detector contained two signals: the d.c. which corresponded to reflectance of the material $R$, and a.c. was the change in reflectance produced by the modulation of surface mirror temperature. Both signals coming from silicon photodiode were measured by means of a lock-in amplifier using two-channel mode of operation. A schematic diagram of the mapping system is presented in Fig. 1.

The beam spot and the laser facet were observed with CCD video camera and monitored under high magnification, which allowed accurate probing of specific regions of the laser. The mapping system was controlled by software written in LabView, which allowed real time monitoring of local mirror temperature. Most of the results were obtained for system with He-Ne laser as a source of probe beam, however any laser source emitting high quality beam might be used instead. Decreasing wavelength of the probe beam causes spatial resolution to increase and points out details connected with material sequence of the laser structure. Moreover, choosing appropriate wavelength of probe beam allows avoiding parasitical signal arising from AR/HR mirror coatings [6].

## 4. Results

The map presented shows temperature distribution on the surface of the front facet of the unstable resonator EF 2/5 laser (Fig. 2). The epitaxial layer sequence of laser diode was a molecular beam epitaxy (MBE)-grown graded-index separate-confinement heterostructure (GRINSCH). The active region consists of an 8 nm thick compressively strained $In_{0.2}Ga_{0.8}As$ single quantum well, which was surrounded by 10 nm thick GaAs spacing layers, followed by doped AlGaAs grading and cladding layers. The *p*- and *n*-dopands were C and Si, respectively. The emission wavelength was in the range of 980 nm. The device was mounted *p*-up on the C-mount type heat sink. The front and rear facets were uncoated. The cavity length equalled 1000 μm. The threshold current of the laser was 310 mA, and power emitted under the pumping current of the value of 1 A (CW regime) was 255 mW.

The map of the front mirror (Fig. 2**b**) was taken for the current of $I = 600$ mA. Temperature distribution maps showed relatively low temperatures for that value of current indicating low absorption and surface recombination rate at the laser mirror.

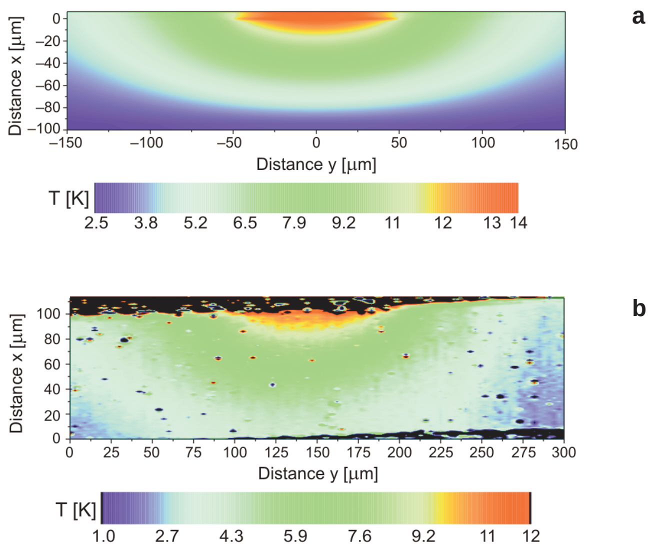


Fig. 2. Calculated (**a**) and measured (**b**) 2-D maps of the relative *T* temperature distribution in a *p*-side up mounted broad-area laser.

The temperature increased in every part of the facet, and the increase was particularly rapid in the active region and its surroundings. This is connected with the fact that heat is generated mostly in active region. Heat dissipation spreads into a thick of GaAs substrate towards heat sink, which is placed on the opposite side of the heat source.

Measurements of the spatial temperature profile are also important in high brightness devices where thermally induced refractive index profiles can strongly affect spatial coherence of a laser. The temperature distribution measured exhibits low gradient in the transversal direction of the junction. This makes the lasers less sensitive to the optical instabilities. Another important issue concerning these devices, which is addressed together with this measurement technique, is the mounting and bonding quality and the optimum choice of substrate material for heat removal.

Numerical calculations were developed simultaneously with experimental investigation. The solution to being analogous of that of heat problem was based on analytical solution of stationary, 2-D heat conduction equation $\nabla(\lambda(x)\nabla T(x, y)) = -g(y)$, where $T$ denotes relative temperature, $\lambda$ – thermal conductivity, $g$ – a heat source function, $x$ and $y$ are the transverse and lateral co-ordinates, respectively. The heat conduction equation is subjected to the following boundary conditions: constant temperature at the bottom of the structure, convection cooling at the top, and no heat escape from the side walls [8]. In our case, we assumed that the active layer was the only heat source in the structure.

Example results are shown in Fig. 2, where we present 2-D maps of relative temperature $T$ distribution for $p$-side up mounted InGaAs/GaAs quantum well laser. The calculations are compared with experimental results obtained by thermoreflectance mapping [9].

## 5. Conclusions

A semiconductor laser mirror surface mapping system based on thermoreflectance effect was developed. The SRTR technique has been applied to evaluate the performance of unstable resonator lasers with etched facets created using chemically assisted ion beam etching. Thermoreflectance proved to be an excellent technique for thermal characterization of laser mirrors and allowed finding optimal conditions for laser facets preparation. The monitoring of the temperature of a device also allows determination of the thermal resistance of the laser plus heat sinking arrangement. It is a very good parameter to distinguish between different device packaging and mirror processing technologies.

Thermoreflectance Mapping System (TMS 2005) main features:

– high resolution, nondestructive, contactless mapping of semiconductor laser mirror temperature;

– system designed for low and high power semiconductor VIS/IR lasers (also with AR/HR coatings);

– laser heat sink temperature accurately controlled by means of Peltier cell supported by water cooling system;

– sensitivity < 1 K;

– accuracy of about ±1 K;

– measurement speed 0.5–1 s/point;

– maximum area of the map 300×300 μm;

– spatial resolution 1 μm and 0.6 μm (depending on the probe beam wavelength);

– probe beam wavelength 442 or 632.8 nm;

– minimal step 0.2 μm;

– the system can work as photoluminescence-mapping system after integration with any spectrometer equipped with CCD camera;

– user-friendly software for data acquisition;

– data averaging and smoothing;

– real time temperature monitoring.

The results of the study should contribute to the better understanding of the laser mirror properties and provide guidelines for design and fabrication of lasers with improved performance and reliability. The method itself has a potential for implementation in a laser production line for monitoring mirror quality.

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*Received June 6, 2005*