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Thermoreflectance temperature measurements for optically emitting devices

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ABSTRACT

This work examines the difficulties associated with using optical techniques to measure temperature when the device itself emits a significant level of light over a wide spectrum, making it a challenge to separate the useful measurement signature from the device light emission. The specific situation considered here is that of using a thermoreflectance (TR) thermography approach to characterize the thermal behavior of semiconductor laser devices. A lowpass filter was placed in the optical path to minimize the primary laser irradiation on the TR imaging and then the TR response of the region of interest was determined over a wide range of visible light wavelengths to locate the maximum response. TR measurements performed at the optimal light wavelength successfully provided a submicron-resolution temperature map of the active area of sample lasers.

1. Introduction

Optical methods have been widely used to capture the thermal behavior in areas of interest on microelectronic devices. Such methods have the major benefit of being non-contact and non-invasive and operate by recording the optical energy associated with the material of interest. Methods based on infrared (IR) physics capture the radiation emanating from a hot surface [1], while thermoreflectance (TR) based methods measure the relative change of reflected light resulting from a change in the temperature of a surface [2]. TR methods have been successfully used to characterize the thermal behavior of devices down to the deep submicron levels [3–5].

This article addresses the difficulties associated with using optical measurement techniques when the device of interest emits light over a wide spectrum at levels that are significantly higher than the levels of light used by the measurement technique itself, making it a challenge to separate the useful measurement signature from the light emission of the device. The specific situation considered here is that of using a TR thermography approach to characterize the thermal behavior of high-power semiconductor laser devices. Like all lasers, semiconductor lasers exhibit spontaneous emission over a wide spectral range. Once the injection current density rises above the threshold level, the magnitude of this primary emission becomes orders of magnitude higher than those of the broadband spontaneous emissions, but because of the nature of the optical cavity, several secondary longitudinal modes are also emitted. These parasitic modes are two or three orders of magnitude weaker than the primary desirable emission mode, but they still contain enough energy to overwhelm the optical sensor used to measure the thermal field. This work was concerned with investigating an approach to handle the primary and parasitic mode emissions while using the optical TR measurement technique to measure the thermal response of semiconductor laser devices.

Both IR and TR methods have been previously used to thermally characterize semiconductor lasers and diodes. Kozlowska [6] presented an extensive review of the use of IR methods in measuring the temperature fields of active semiconductor lasers. While the IR method was used with success and even showed potential as a screening tool for laser devices, the best spatial resolution reported by Kozlowka, which was on the order of 5 μm, is an order of magnitude lower than what would be required for the types of lasers investigated in the present work. A couple of groups have reported the use of TR to measure the temperature of active lasers in a pointwise manner, where the reflected signal was

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captured either by a single photodetector [7] or by an array of photodetectors [8]. In both cases, the acquisition was locked-in on the modulation of the laser injection current, but the authors did not mention the procedures used to mitigate the irradiation from the laser (primary mode and its harmonics) and then to separate the TR signal of interest from the optical output of the laser itself. As discussed in the present manuscript, the mitigation and separation approaches are crucial for any attempt to obtain useful temperature fields around the lasing region with an optical approach. In a third article, Kendig et al. [9] discussed the use of bandpass filters to attenuate the intensity of the light-emitting diode output, but they were dealing with relatively weak light sources, as opposed to semiconductor lasers.

The devices being investigated in this work are 980 nm chips with a cavity length of 3.9 mm, and are wavelength stabilized for improved performance in Erbium Doped Optical Amplifiers (EDFAs). Wavelength stabilization is obtained by locking the emission wavelength to a Fiber Bragg Grating (FBG) inscribed in the fiber pigtail. Additional details pertaining to the properties and technology of the laser devices can be found in previous papers [10], and references therein, and will therefore not be repeated here. There is significant interest in fully characterizing the thermal behavior of the key operational features of these high-power devices in order to help ensure optimal performance, reliability, and longevity. Because the regions of interest where the temperature fields are sought have essential features in the submicron scales, it made sense to use the TR measurement technique, which makes it possible to achieve those high levels of submicron spatial resolution.

2. Experimental approach

The experimental temperature mapping system used in this work is a TMX Scientific T°Imager™ [11], which is based on the thermoreflectance (TR) method, where the change in the surface temperature is measured by detecting the change in the reflectivity of the sample. A photo and functional schematic of the thermoreflectance thermography (TRTG) system are shown in Fig. 1. The measurement methodology involves a calibration phase and a device activation phase, which have been detailed in previous publications. In the calibration phase, the thermoreflectance coefficient, $C_{TR}=(\Delta R/R)/\Delta T$, is determined for each of the surface materials in the region of interest at a given wavelength of light. The activation phase yields the relative change in surface reflectivity ($\Delta R/R$) in that region of interest. Calculating the temperature rise map (ΔT) over the DUT becomes simply an exercise of scaling the relative change in surface reflectivity ($\Delta R/R$) with the corresponding calibration data (C_{TR}) for each surface of interest. The thermoreflectance method has been described in great detail in previous papers [2–5], and the interested reader is referred to the review paper [2], containing an extensive list of references that will not be repeated here.

Three structurally similar laser devices of the type described above were used in this investigation and will be referred to simply as Lasers A–C. Fig. 2 shows a high-magnification top view image of the region of interest on the device, with an indication of the direction of laser emission which is perpendicular to the camera view axis. A yellow dashed rectangle delineates the zoom-in area where results will typically be shown in this work. This orientation was chosen for two important reasons: first, to minimize the direct exposure of the camera sensor to the laser light since the latter is not of interest, and second, to allow the thermoreflectance system to capture the active semiconductor region where the light and associated heat are being generated.

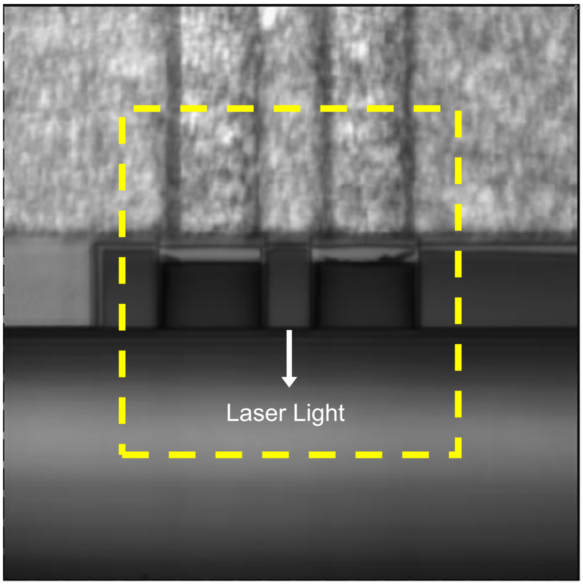

Fig. 2. Top view image of DUT with active area at the center. Laser light emits at 90° to the TR camera measurement axis.

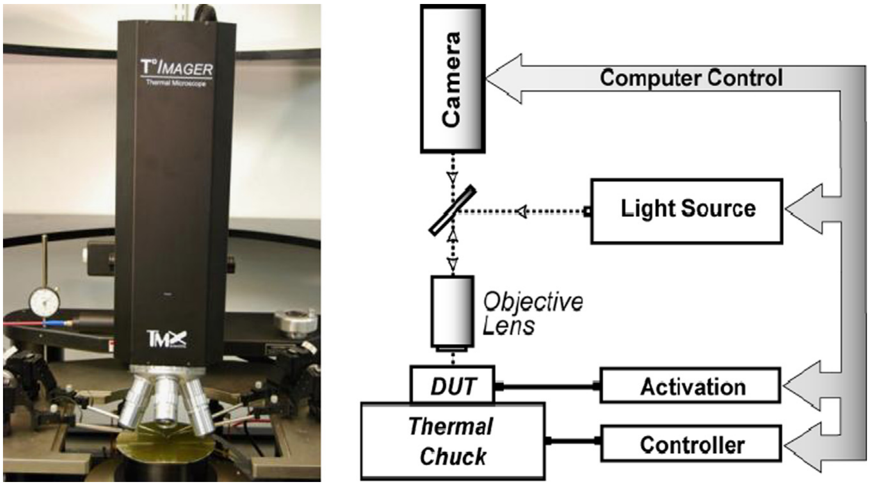

Fig. 1. Photo and functional schematic of thermoreflectance thermography (TRTG) system.