High Spatial Resolution Thermal Imaging of Multiple Section Semiconductor Lasers

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Abstract

Temperature strongly affects output power and peak wavelength characteristics of active optoelectronic devices. In this paper we describe how thermoreflectance imaging technique can be used to obtain thermal maps of photonic devices under operation. Submicron spatial resolution and <0.1C temperature resolution has been achieved. Temperature non-uniformity is investigated in various multi section lasers and photonic integrated circuits. It is shown that large temperature variations can be developed over small regions on the order of 20-30μm in diameter. By optimizing the thermal design of the device, we have achieved record level of damage free power dissipation in electro-absorption modulators integrated with multiple section lasers.

Introduction

Temperature stabilization is very important for optoelectronic devices such as laser sources, switching/routing elements, and detectors. This is especially true in current high speed and wavelength division multiplexed (WDM) optical communication networks. Long haul optical transmission systems operating around 1.55 μm typically use Erbium doped fiber amplifiers (EDFA's), and are restricted in the wavelengths they can use due to the finite bandwidth of these amplifiers. As more channels are packed into this wavelength window, the spacing between adjacent channels becomes smaller and wavelength drift becomes very important. Temperature variations are the primary cause in the wavelength drift, and also affect the threshold current and output power in laser sources. Most stable sources such as distributed feedback (DFB) lasers and vertical cavity surface emitting lasers (VCSEL's) can generate large heat power densities on the order of kW/cm^2 over areas as small as 100 μm^2 [1,2]. The output power for a typical DFB laser changes by approximately 0.4 dB/°C. Typical temperature-dependent wavelength shifts for these laser sources are on the order of 0.1 nm/°C [3]. Therefore a temperature change of only a few degrees in a WDM system with a channel spacing of 0.2-0.4 nm would be enough to switch data from one channel to the adjacent one, and even less of a temperature change could dramatically increase the crosstalk between two channels. Temperature stabilization or refrigeration is commonly performed with conventional thermoelectric (TE) coolers. However since their integration with optoelectronic devices is difficult [1,4], component cost is greatly increased because of packaging. The reliability and lifetime of packaged modules is also usually limited by the TE cooler [5]. In addition, when several devices are monolithically integrated in optoelectronic integrated circuits (OEICs), temperature across the chip can become non-uniform. Recently, thin film micro refrigerators have been studied extensively [6,7,8]. They are attractive elements that could be used to control temperature of individual devices on a chip. They have achieved cooling power densities exceeding $500W/cm^2$ and response times below 20-30μs [8]. In order to improve thermal design of OEICs, it is very useful to identify hot spots in the chip. In this paper we present experimental results for the temperature distribution in multi section distributed Bragg reflector semiconductor laser structures and integrated electro-absorption modulators.

Integrated electroabsorption modulator is very attractive for high-speed modulation applications. In this modulator (which is just a reverse-biased pn junction), light intensity is decaying exponentially along the device. This can create non-uniform temperature distribution [9]. Since most of the optical power is absorbed over a very small region, large heating is produced which can damage the device. With an optimized design, we show that we can limit modulator heating to less than **10C** under normal operating conditions.

In the following we will describe the experimental setup for thermoreflectance imaging and show temperature profile for multi section semiconductor laser structures and integrated electroabsorption modulators under operating conditions.

Experimental setup

We studied theoretically and experimentally various non-contact methods to measure temperature with sub micron spatial resolution in electronic and optoelectronic devices. Trials with commercial thermal microscopes based on cryogenically cooled InSb or HgCdTe focal plane arrays provided poor temperature (>5-10C) and spatial resolution (>5 micron). This is mainly due to the fact that semiconductor substrate and metallic interconnects on top of it are far from "black body" as they are highly reflective. The technique that seemed most promising was thermoreflectance. The temperature profile is determined by measuring the temperature-induced change in the surface reflectivity. A lock-in technique is needed to detect the small change in the reflectivity. Based on this method we have achieved thermal imaging of active electronic devices with submicron spatial resolution and <0.1C temperature resolution [10].

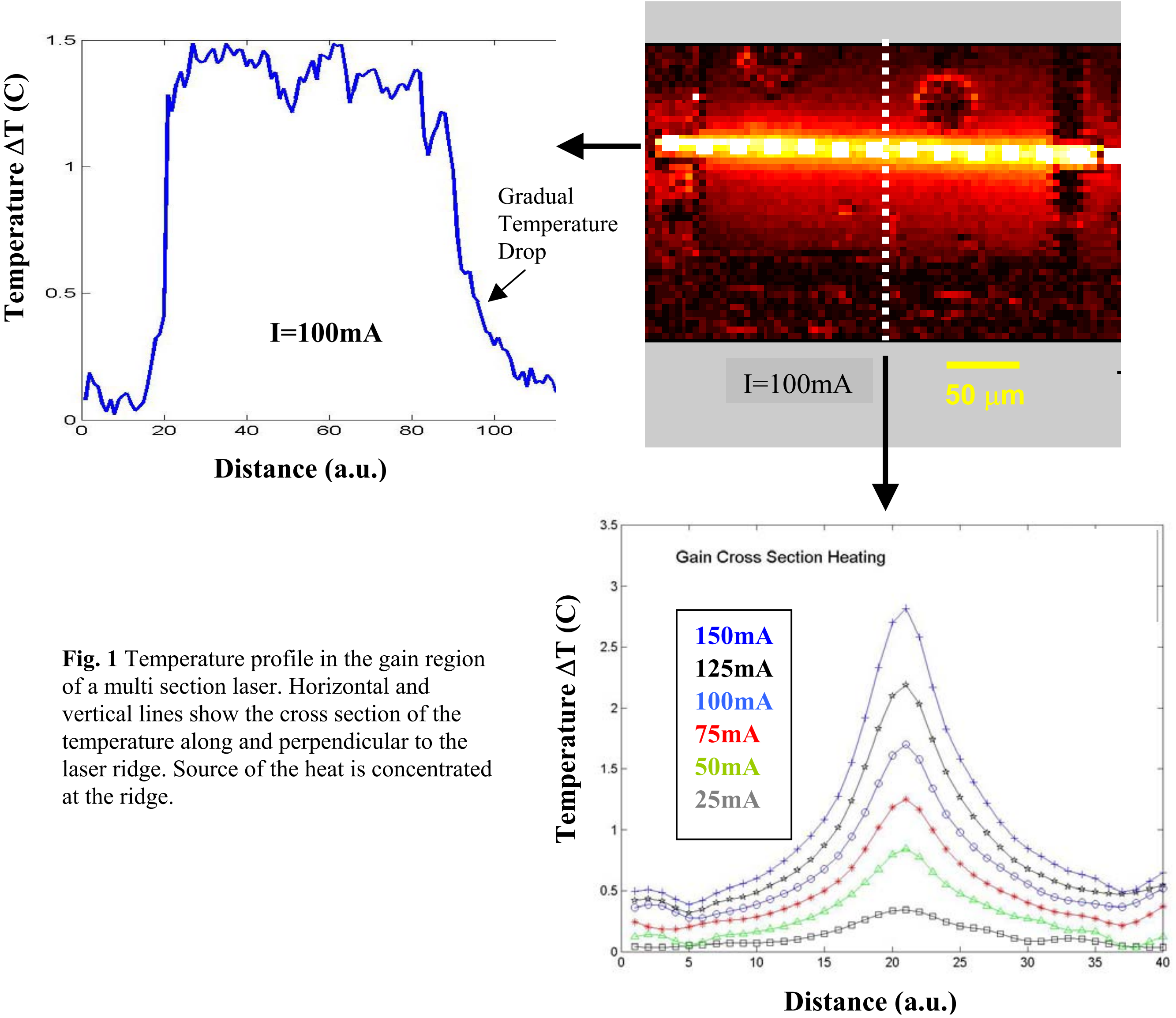

Fig. 1 Temperature profile in the gain region of a multi section laser. Horizontal and vertical lines show the cross section of the temperature along and perpendicular to the laser ridge. Source of the heat is concentrated at the ridge.

Calibration of the thermoreflectance coefficient was done using a method outlined by Dilhaire et al. [11] and also using micro thermocouples. The thermoreflectance coefficient value of 8.1e-5 /K was obtained for the gold surface and a value of -4.7e-5 /K was obtained for the InP substrate material. Using these coefficients, the change in the reflection coefficient is measured and related to the surface temperature. The measurements were performed on the gain region of a multi section laser structure. Fig. 1 displays the temperature profile along and perpendicular to the laser ridge under different biasing conditions. It can be seen that, as expected, source of the heat is concentrated at the laser ridge. It is interesting to note that temperature drop along the laser ridge is not symmetric. This can be used to study thermal cross talk between adjacent sections or fabrication errors due to imperfect electrical isolation of neighboring devices. The overall heating on the laser ridge is on the order of 3C for a bias current of 150mA. Figure 2 shows a picture of an electroabsorption modulator integrated with a semiconductor laser, along with thermal images taken at a bias of –2.8V and 0V. The modulator is formed of a thick (0.4 micron) quaternary layer emitting at 1.4 micron. It is surrounded by p and n type InP.

3. Results/Discussion

Generally in an absorbing medium, the intensity of the light as a function of position is given by the decaying exponential: $I(x)=I_o\exp(-\alpha x)$. If we make the reasonable assumption that the dominant cause of heating in the modulator is caused by the photocurrent absorbed at that position, the surface temperature should be proportional to the change in light intensity along the modulator. At small light intensities and modulator biases, surface temperature measurement can provide information of how the absorption coefficient inside the modulator is changing with external parameters. This is an attractive way to characterize individual elements of an optoelectronic integrated circuit directly on a chip [12]. Figure 3 displays the surface temperature distribution along the modulator with 35mW

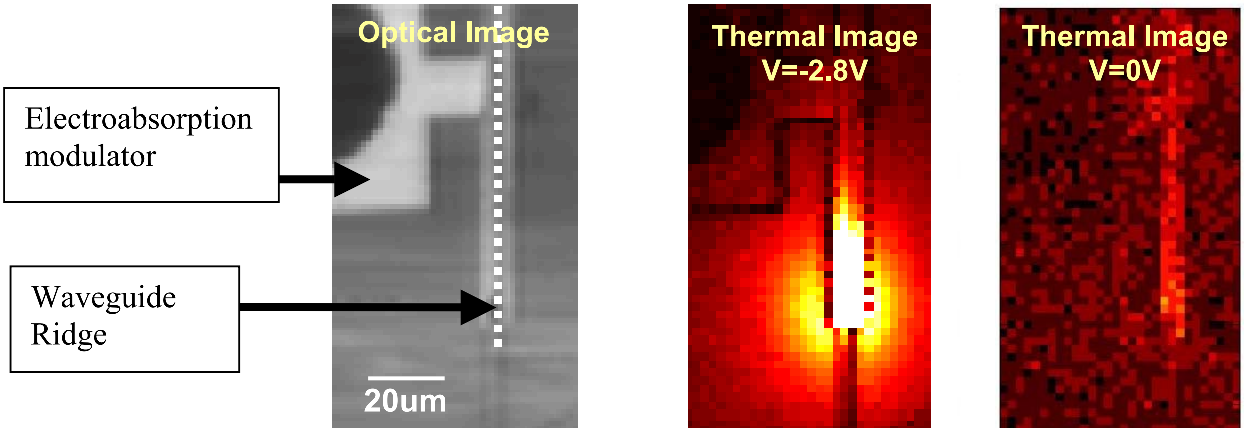

Fig 2. Optical and thermal image of an electroabsorption modulator at V=-2.8V and V= 0V. The dotted line indicates the position of the line scans used in subsequent graphs.

input power. There is a severe non-linearity in the change of the absorption coefficient between 2.75 and 2.77 applied modulator bias. Surface temperature can increase by 110C in a region as small as 20-30µm. We believe this is caused by the increase in the absorption coefficient with temperature, which leads to increased absorption at the beginning of the modulator and thermal runaway. It is interesting to note cross over in the temperature distribution at the distance of ~25µm. Points farther away in the modulator are actually cooler at high biases. This is due to the fact that most of the light is absorbed at the beginning of modulator. By improving the thermal design of the device one can avoid this thermal run away. Fig. 4 shows the temperature distribution for the same electroabsoption modulator with improved junction-to-the-case thermal resistance. The surface temperature of the modulator is significantly reduced and much larger voltages can be applied. Measurements of the maximum allowed dissipated power (photocurrent times bias voltage) indicate damage free operation is obtained for more than 300 mW of dissipated electrical power.

Conclusions

In order to improve thermal design of OEICs, it is very useful to identify hot spots and thermal crosstalk in the chip. In this paper we described how thermoreflectance imaging technique is used to obtain thermal maps of photonic devices under operation. Submicron spatial resolution and <0.1C temperature resolution has been achieved. Temperature distribution in multi section semiconductor laser structures and integrated electro-absorption modulators have been measured. We have shown that high power operation can be achieved with a record dissipated power limit of more than 300 mW.

Acknowledgments

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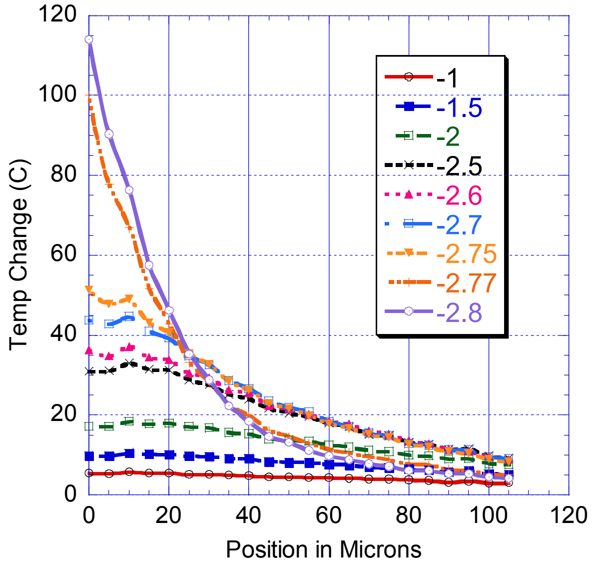

Fig 3. Temperature distribution along the device for different modulator biases under high input power conditions (35 mW). Heating increases substantially between -2.75V and –2.77V applied modulator voltage.

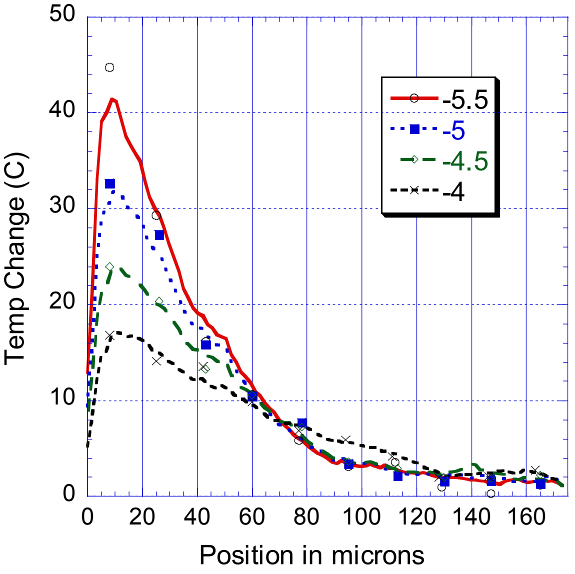

Fig 4. Temperature distribution along the device with improved thermal design for different modulator biases under high input power conditions. Note that much lower temperatures are achieved at higher modulator biases.

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