Simulation of Thermal Tuning in V-coupled Cavity Laser with an On-chip Thin-film Heater

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Abstract— We present the design and simulation results of a thermally tuned V-coupled cavity laser (VCCL) with an on-chip heater. A thermal model based on finite-element method (FEM) is developed to calculate the transient and steady-state temperature distribution in the laser. The wavelength tuning behavior is simulated. The compact gratingless widely-tunable semiconductor laser is promising for reconfigurable optical networks as well for laser sensing.

1. INTRODUCTION

With the progress in reconfigurable optical communication network and laser sensing, tunable semiconductor lasers with high performances in terms of single-mode characteristics, wavelength-tuning as well as high reliability, low-cost and operational simplicity are highly desirable. V-coupled cavity laser (VCCL) is a compact, gratingless widely-tunable semiconductor [1] that does not require epitaxial regrowth, and can achieve single-electrode controlled wide wavelength with an excellent SMSR [2].

Adjusting the temperature of the whole laser including its carrier by thermo-electric cooler (TEC) can increase the tuning range of the VCCL [3, 4], but the tuning time and efficiency is not ideal for practical use because of the long distance between the light emitting region and the heat source. To solve that, we present a thermal tuning method using on-chip heaters [5] for VCCL. Simulation results of its tuning behavior are provided and discussed in this paper.

2. DEVICE DESCRIPTION AND TUNING MECHANISM

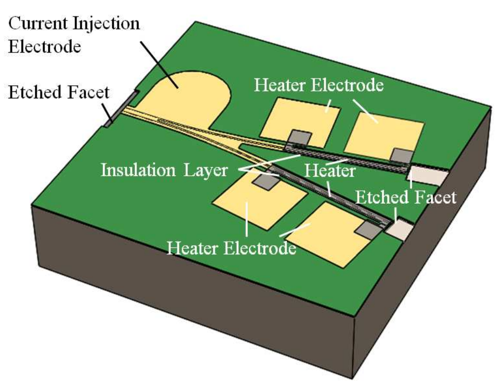


Figure 1: Schematic diagram of the VCCL with on-chip heater.

Figure 1 is the schematic structure of the VCCL with a thin-film heater. The laser is produced on an InP-based epitaxial wafer that includes 5 InGaAsP quantum-wells active region. The V-coupled cavity consists of two waveguides coupled through a reflective 2×2 half-wave coupler, forming a V-shaped geometry, bounded by etched facets. A layer of SiO_2 is patterned after the electrodes are fabricated, to insulate the p-electrodes from the heater. Finally, a NiCr film is deposited on the SiO_2 film to serve as the heater.

Thermal wavelength tuning can be accomplished by adjusting current injection into one of the heaters. The Joule-heat generated in the energized heater is conducted to the waveguide and changes its refractive index due to thermo-optic effect. Consequently, the resonant peaks of the cavity varies and the wavelength of output laser is tuned by employing the Vernier effect.

3. HEAT TRANSFER IN THE LASER

A heat-transfer model for an InP-based V-coupled cavity laser (VCCL) is first developed, where steady-state and time-dependent temperature distribution of the device is studied by using finite element method (FEM).

To simplify the model, we assume that the temperature variation along the waveguide is negligible. Therefore, the 2-dimensional temperature distribution in the cross-section perpendicular to the waveguide can represent the temperature distribution in the whole laser. Besides, an equivalent InGaAsP layer is used to represent the active region including 5 InGaAsP quantum-wells and the GRIN-SCH layers, thus enhancing the computing efficiency. Fig. 2 illustrates the 2-D model of the VCCL with top-heating structure. The heat sink and solder on which the laser chip is placed are included in the thermal model as well.

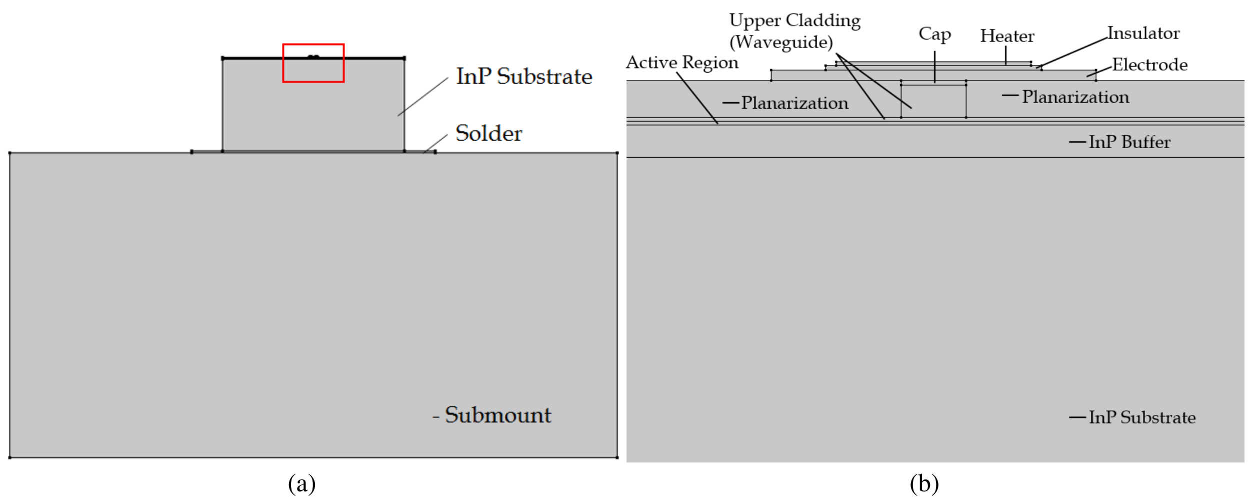
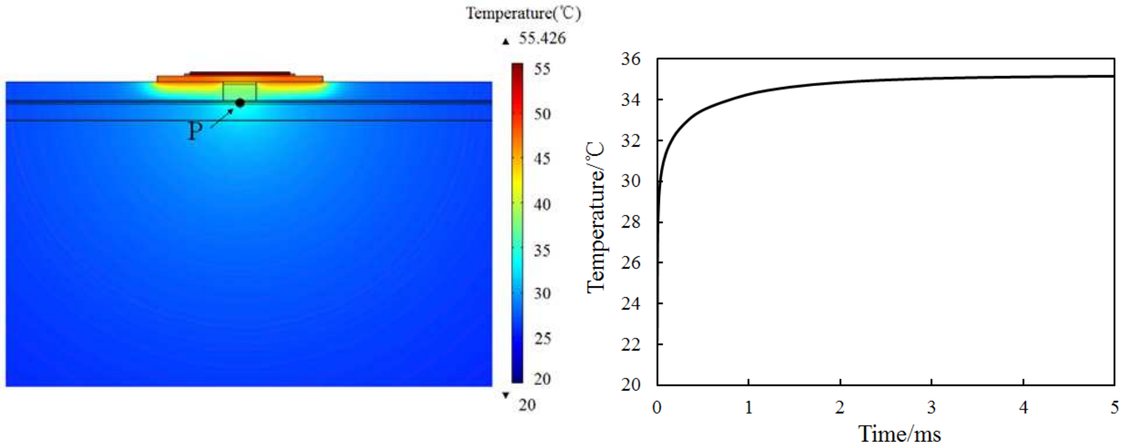


Figure 2: 2-D model of the VCCL with top-heating structure; (a) whole model including submount and solder and (b) magnified picture of the part in red box in (a).

The thermal model is constructed using the "Heat Transfer in Solids" module of COMSOL software. The structure and material parameters used in the model are defined in Table 1. We define the initial condition as 20°C in all domains in the model. The boundary condition is: 20°C for the bottom surface of the heat sink, and a heat exchange boundary of $h = 5\,\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$ with temperature of 20°C in the adjacent environment for all other surfaces. With the heat generation rate of 100 mW in the heater, we can solve the transient heat-transfer equation [6] numerically using FEM.

Table 1: Material parameters used for thermal model.

Layer	Material	Density $\rho(\mathrm{kg{\cdot}m^3})$	Specific heat capacity $C_p(\mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}})$	thermal conductivity $\mathrm{k(W{\cdot}m^{-1}{\cdot}K^{-1})}$
Submount	AlN	3240	743	285
Solder	$Au_{80}Se_{20}$	14500	137.88	57
Substrate, buffer, upper cladding	InP	4790	49.1	68
Active region	InGaAsP	5500	250	13.7
Cap	InGaAs	5500	350	5
Planarization	SU8	1214	1500	0.3
Electrode	Au	19300	129	327
Insulator	SiO_2	2200	730	1.4
Thin-film heater	Nichrome	8529	12.6	11.2



(a) (b)

Figure 3: (a) 2-D temperature (degC) distribution at steady state of the laser with top-heating structure after 100mW heat provided in the heater; (b) temperature variation of probe P with time.

Figure 3(a) shows the model structure and the 2-D temperature distribution when the temperature reaches steady state. To observe the temperature variation in the active region over time, the center point P of the active region as shown in Fig. 3(a), is set as a probe. The temperature at the point P as a function of time is shown in Fig. 3(b), which indicates that the active region in the heated waveguide has a temperature increase of 15 K after 100 mW heating source power is provided on the heater. The time duration to reach a thermal balance is around 2 ms, which gives sufficiently high tuning speed for many applications.

4. THERMAL CROSSTALK AND TUNING RATE

During thermal tuning of the VCCL with heater, we change the temperature of the cavity supposed to be heated, while hoping the temperature in the other cavity to increase as weakly as possible. However, it is inevitable that heat spreads from the tuning cavity to the other one, which will reduce the thermal-tuning efficiency.

Heat spreading between the two waveguides of the VCCL was calculated using the 2-D finite element model. Considering that the space between the two cavities differs from 40 μm to 110 μm linearly, we assume the model of two parallel waveguides with a distance of 75 μm and length of 200 μm can approximately represent the heat transfer in VCCL. Fig. 4(a) shows the thermal model in the cross-section perpendicular to the center line of the VCCL and the calculated steady-state temperature distribution with 100 mW heat source provided in the heater on the left. Two temperature probes A and B are set at the center of the active region in the left and right cavities, respectively.

Figure 4(b) shows the temperature profile along the horizontal line in the center of the active region in Fig. 4(a). The thermal crosstalk is defined as the rate of temperature increase of probe B over that of probe A. In this example, probe A obtains a temperature rise of 15 K, while probe B obtains only 4 K, which gives the thermal crosstalk of 26.9%.

Considering the temperature induced wavelength tuning of about 0.1 nm/K due to refractive index variation, the 11 K temperature distinction will cause 1.1 nm wavelength shift difference between the resonant peaks of the two cavities, and 22 nm wavelength shift of the output laser due to the Vernier effect of the VCCL with 5% difference in cavity lengths. This theoretical tuning rate of 0.22 nm/mW is much more power-efficient than tuning by thermal-electric cooler (TEC).

5. ANALYSIS OF THERMAL INSULATING GROOVE

Etching a slot beside the heated waveguide to act as the thermal insulating groove is a convenient method to suppress thermal crosstalk and improve thermal tuning efficiency [7]. We evaluated the effect of the thermal insulating groove between the two cavities of VCCL, using the model as shown in Fig. 5(a).

The calculated thermal crosstalk as a function of the groove's depth scanned from 0 μm to 50 μm is as shown in Fig. 5(b). It is found that the crosstalk cannot be reduced to below 20% unless

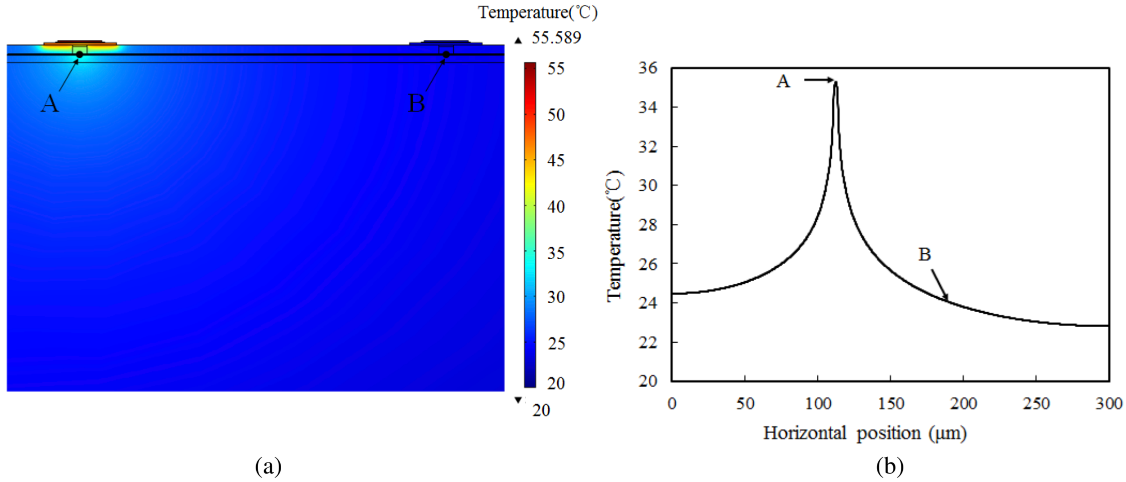


Figure 4: (a) 2-D steady state temperature (degC) distribution in the cross-section of VCCL with top-heating structure after 100mW heat source provided in the heater on the left; (b) temperature (degC) distribution along the horizontal line in (a) in the center of the active region.

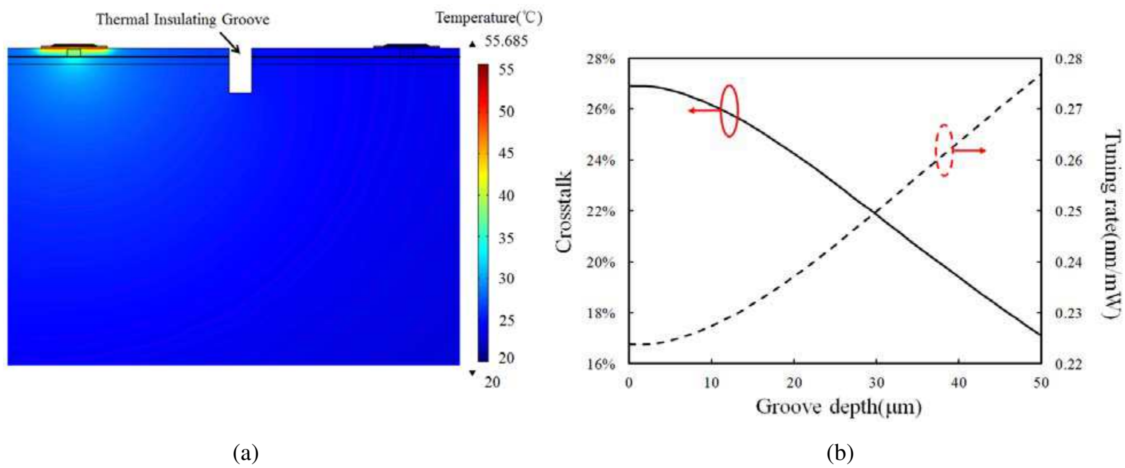


Figure 5: (a) 2-D thermal model with 10 μm deep thermal insulating groove and the steady-state temperature distribution ; (b) thermal crosstalk (solid) and tuning rage (dashed) as a function of depth of the thermal insulating groove.

the groove is deeper than 37 μm. With the etching depth of the groove increased to 50 μm, the crosstalk decreases to 17%, and the tuning rate increases to 0.28 nm/mW. Since such etching depth is usually unrealistic in monolithic devices, it is reasonable to conclude that the groove can hardly improve the thermal tuning efficiency.

6. CONCLUSION

We have developed a thermal model of the VCCL with on-chip thin-film heaters, using 2-D FEM. The calculation indicates that the heated waveguide obtains a balanced temperature increase of 15 K in 2 ms after 100 mW heat generation rate is provided on the heater on top. The thermal crosstalk is 26.9% between the two cavities of the VCCL, which gives the theoretical thermal tuning rate of 0.22 nm/mW in a VCCL with 5% difference in cavity lengths. The thermal crosstalk cannot be obviously suppressed with thermal insulating groove. These results reveals that thermal tuning of VCCL using on-chip heater is a reliable and convenient wavelength tuning method, which provides sufficiently high tuning efficiency and tuning speed for many applications.

ACKNOWLEDGMENT

This work was supported by the National High-Tech R&D Program of China (grant No. 2013AA014 401).

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