Electro-thermal Single-mode Tuning in Field-Induced Charge-Separation Lasers

Chin-Han Lin[1], Yan Zheng[1], Leif A. Johansson[1], Mark J. W. Rodwell[1], and Larry A. Coldren[1,2]

[1]*Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106, USA*

[2]*Department of Materials, University of California, Santa Barbara, CA 93106, USA*

Phone: 1-805-893-7065 Fax: 1-805-893-4500 Email: chinhan@ece.ucsb.edu

Abstract – We demonstrate the wavelength tunability via electro-thermal effect of field-induced charge-separation lasers (FICSLs). A large 6.6 nm tuning range is achieved with only 4.6 mA of tuning current. This high tuning efficiency persists up to about 40 kHz.

I. Introduction

We have demonstrated a novel Field-Induced Charge-Separation Laser (FICSL) in a Vertical-Cavity Surface-Emitting Laser (VCSEL) embodiment, which promises to increase the modulation bandwidth via modulating the gain directly [1][2]. Recently, it was discovered that by adding the doping in the off-state well to decrease the minority carrier lifetime, the non-radiative recombination rate in this region could be increased. As a result, an intra-cavity electro-thermal tuning region was formed where electrons and holes recombined and emitted phonon energy. This enables FICSLs to be operated as a tunable VCSEL for wavelength division multiplexing (WDM) systems, complementing the well-studied MEMS tunable VCSELs [3][4] as well as other electro-thermal tunable VCSELs [5].

II. Intra-cavity electro-thermal tuning region

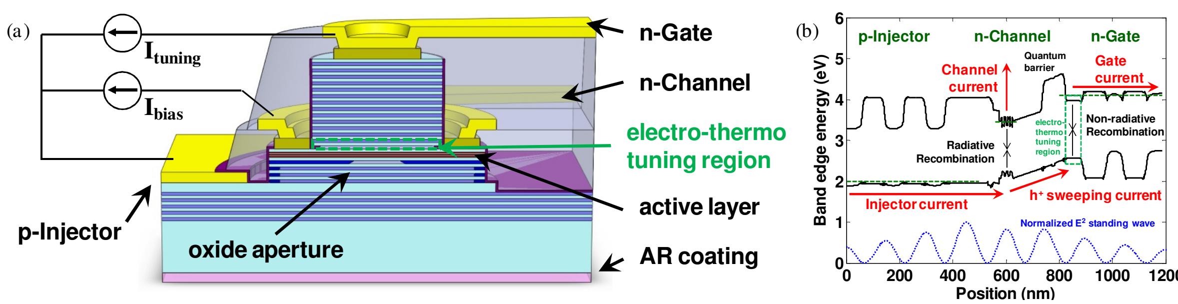

Fig. 1. (a) Schematic of a FICSL showing an intra-cavity electro-thermo tuning region (b) Band diagram showing different current flows

The schematic of a FICSL is shown in Fig. 1a, with the one-dimensional band-edge diagram near the active region along the longitudinal direction shown in Fig. 1b. To separate electrons and holes, a quantum barrier was deliberately created through bandgap engineering. When a gate bias is applied, holes are driven away from the quantum well into the off-state well, and start to accumulate. As the off-state well is doped n-type, holes and electrons will recombine at a rate determined by the doping level. This recombination rate can be pre-determined by material growth: the higher the n-doping is, the shorter the minority carrier (hole) lifetime, and the higher the recombination rate will be.

At equilibrium, electrons and holes consumed by binomial recombination have to be replenished from the gate and the injector respectively. According to Kirchhoff's circuit law, the hole current flowing into the off-state well has to be equal to the electron current supplied by the gate, and equal to the recombination current in the off-state well. The hole current coming from the injector will be split into two streams: the radiative recombination current which contributes to the lasing mode, as well as the hole sweeping current into the off-state well. As the optical output power was predominantly determined by the radiative recombination in the quantum wells, the non-radiative recombination in the off-state change the lattice temperature in proximity, resulting in an index change as well as a cavity mode shift. The lasing wavelength will be tuned as a result.

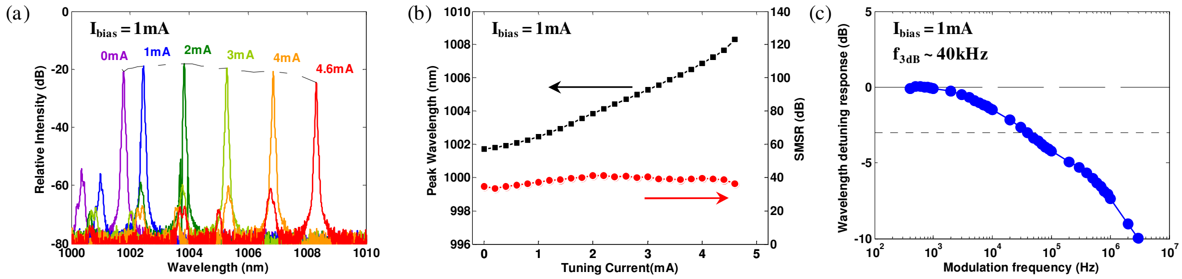

Fig. 2. Room temperature wavelength tuning of a 3 μm device with I_{bias} = 1 mA (a) lasing spectra with different I_{tuning}. (b) Peak wavelength and side mode suppression ratio (SMSR) vs. I_{tuning}. (c) Dynamic tuning characteristics with a cut-off frequency f_{3dB} ~ 40 kHz.

III. Device Design

To demonstrate the tuning effect, A p-i-n-i-n three-terminal device was grown and fabricated, similar to the structure reported before [1]. The doping level in the off-state well was increased to reduce the hole life-time and promote recombination. Devices with smaller oxide apertures were fabricated to suppress side modes and allow single-mode operation.

IV. Experimental Results

Two current sources were required for characterization: one for the constant bias current, I_{bias}, and the other for the variable tuning current, I_{tuning}, with the configuration shown in Fig. 1a. A device with a 3 μm aperture was chosen as it operated with single-mode up to 1.6 mA of I_{bias}. The spectra were recorded by an optical spectrum analyzer (OSA) with the side-mode suppression ratio (SMSR) calculated accordingly. Fig. 2a shows the lasing spectra, and Fig. 2b shows the peak wavelengths and SMSRs with different I_{tuning}. A continuous tuning of 6.6 nm was achieved with 0 to 4.6 mA of tuning current, while the device maintained single-mode within this tuning range. The wavelength change versus stage temperature was characterized to be 0.0698 nm/°C.

The dynamic characterization was performed by driving the device with a sinusoidal I_{tuning} with a function generator. The wavelength detuning was then determined by the spacing between the two major peaks on the OSA. For the 3 μm device, the detuning at low frequencies was around 1.69 nm. At high frequencies, this mode spacing decreased with a 3dB cut-off frequency around 40 KHz, as shown in Fig. 2c.

V. Conclusion

We have demonstrated the electro-thermo wavelength tuning model for FICSLs. The minority carrier lifetime in the off-state well was reduced by doping to accelerate non-radiative recombination, creating an intra-cavity electro-thermo tuning region to change the cavity mode location. Both static and dynamic experimental results were presented, showing large tuning range with single mode operation.

Acknowledgement

This work was supported by DARPA through a STTR with Ziva Corp. and by NSF through a GOALI program. A portion of this work was done in the UCSB nanofabrication facility, part of the NSF funded NNIN network.

References

[1] C.-H. Lin, Y. Zheng, M. J. W. Rodwell, L. A. Coldren, *22nd IEEE International Semiconductor Laser Conference*, PD2 (2010).

[2] C.-H. Lin, Y. Zheng, M. Gross, M. J. W. Rodwell, L. A. Coldren, *Proc. Optical Fiber Communication Conference*, OWD5 (2011).

[3] C. J. Chang-Hasnain, *IEEE Journal of Selected Topics in Quantum Electronics*, vol.6, no. 6, pp. 978-987 (2000).

[4] C. Gierl, T. Gruendl, P. Debernardi, K. Zogal, C. Grasse, H. A. Davani, G. Böhm, S. Jatta, F. Küppers, P. Meißner, and M.-C. Amann, *Optics Express*, vol. 19, no. 18, pp. 17336-17343 (2011).

[5] Y. Uchiyama, T. Kondo, K. Takeda, A. Matsutani, T. Uchida, T. Miyamoto, and F. Koyama, *Japanese Journal of Applied Physics*, vol. 44, pp. L214-L215 (2005).