High Efficiency Operation of Membrane Distributed-Reflector Laser with Reduced Index Coupling Coefficient Structure

Takuo Hiratani[1], Daisuke Inoue[1], Takahiro Tomiyasu[1], Kai Fukuda[1], Nagisa Nakamura[1]
Tomohiro Amemiya[1,2] Nobuhiko Nishiyama[1,2], and Shigehisa Arai[1,2]
[1]Department of Electrical and Electronic Engineering, Tokyo Institute of Technology
[2]Institute of Innovative Research (IIR), Tokyo Institute of Technology
e-mail: arai@pe.titech.ac.jp

***Abstract*—High efficiency operation of membrane distributed-reflector laser was demonstrated by both an improvement in differential quantum efficiency and a reduction of differential resistance. A threshold current of 0.44 mA, an external differential quantum efficiency for the front-side output of 36%, and a maximum power conversion efficiency of 14.6% were obtained for a device with a DFB section length of 40 µm.**

Keywords—semiconductor laser; optical interconnect; membrane laser; DR laser

I. Introduction

The optical interconnect is one of the attractive solutions for low-power consumption and high-density communications. Recently, this technology was applied to super-computers and huge systems in data centers. Various investigations of introducing on-chip optical interconnection to LSI have been widely conducted [1]. Behind this background, there are various problems in the global interconnects of LSI such as signal delay, Joule heating, and large power dissipation [2], [3], which limits the performance of LSI. In order to realize the on-chip optical interconnection, light sources with ultra-low power consumption are required. For such optical links, an energy cost of less than 100 fJ/bit was required for the global interconnect [4].

As candidates for such applications, we proposed and demonstrated low-power consumption lasers based on the semiconductor membrane structure [5],[6] for membrane photonic integrated circuits (MPICs) on LSI. Although low threshold current operation, asymmetric light output characteristics, and 10 Gb/s direct modulation with low bias current were realized [7]-[9], the power conversion efficiency was poor because of the low differential quantum efficiency and the high series resistance. In this work, we could achieve an unprecedented power conversion efficiency by an improvement in differential quantum efficiency as well as a reduction of series resistance.

II. Device Structure and Fabrication

Fig.1 shows the schematic structure of the membrane distributed-reflector (DR) laser, which consists of an active

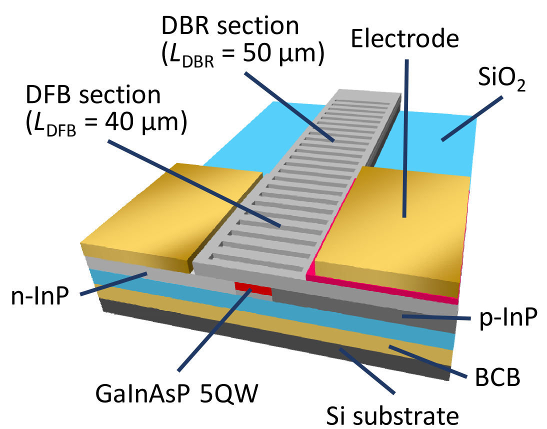

Fig. 1 Schematic structure of the membrane DR laser.

distributed-feedback (DFB) section and a passive distributed-Bragg-reflector (DBR) section. The integrated DBR enhances the light output power from the front side. In this work, we designed the grating with a relatively low index-coupling structure; i.e., the index-coupling coefficient was reduced to around 1000 cm^{-1} so as to reduce scattering from the grating regions. In order to match the lasing wavelength and the Bragg wavelength in the DBR section, the periods of the DFB and DBR sections were set to 291 nm and 293 nm, respectively.

The initial wafer with a 270 nm-thick core layer, including 5 GaInAsP quantum-wells (5QWs) and etch stop layers on the *n*-InP substrate, was prepared for fabrication. Firstly, GaInAsP with a bandgap wavelength of 1.22 µm was regrown to form the passive waveguide structure by organometallic vapor-phase-epitaxy (OMVPE). Next, lateral-current-injection (LCI) structure was formed by two-step regrowth of *n*-InP and *p*-InP side cladding layers. After depositing a 1 µm-thick SiO_2 cladding, the laser wafer was bonded upside down on a BCB coated Si host substrate. Then, the etch stop layers were removed and Au/Zn/Au/Ti/Au for the *p*-electrode and Ti/Au for the *n*-electrode were evaporated. Finally, the surface gratings for both the DFB and DBR sections were formed by electron beam lithography and wet chemical etching; and the

This work was supported by JSPS KAKENHI grants numbered #15H05763, #25709026, #15J04654, #15J11776, and #16H06082, and also by JST-CREST.

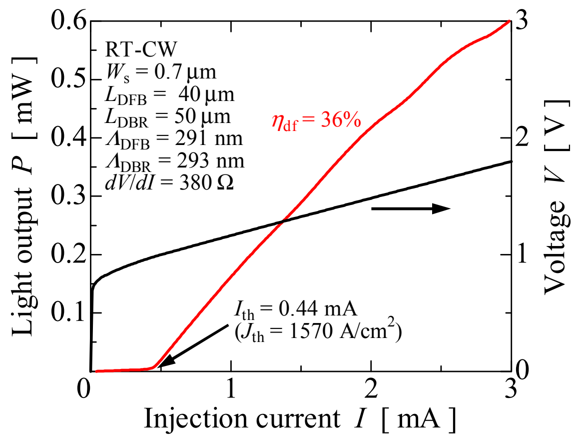

Fig. 2 Current-light output and current-voltage characteristics of the fabricated membrane DR laser.

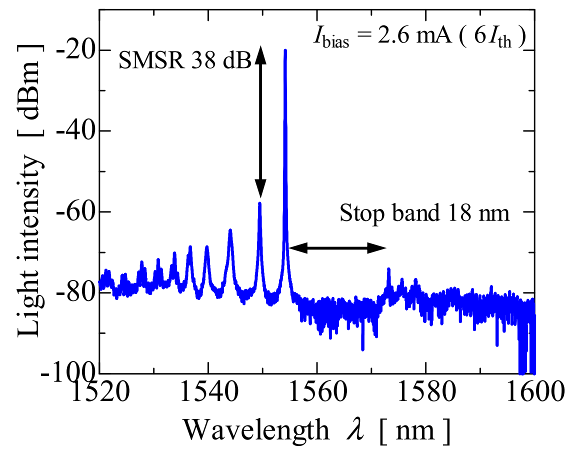

Fig. 3 Lasing spectrum of the fabricated membrane DR laser.

semiconductor layer on both sides of the passive waveguide was etched to suppress the leakage current. Both facets of the device were cleaved for measurement, with no coating.

III. Measurement Results

Static characteristics of the fabricated membrane DR laser with a stripe width of 0.7 µm, a DFB section length of 40 µm and a DBR section length of 50 µm were measured. Fig. 2 shows the current-light output (*I-L*) and current-voltage (*I-V*) characteristics of the membrane DR laser. A threshold current of 0.44 mA (corresponding to a threshold current density of 1570 A/cm^2) and an external differential quantum efficiency for the front-side output of 36% were obtained. This efficiency is around 2 times higher than that of our previous work [8]. The required light output power of 0.16 mW for 10 Gb/s operation [10] was obtained at a bias current of 1 mA. Furthermore, a threshold voltage of 0.98 V and a differential resistance of 380 Ω at the threshold current were obtained. The differential resistance was reduced by a reduction of the distance between the *p*-electrode and the active region to 1.6 µm, which is almost half of that of our previous device (3.0 µm). Thanks to these improvements, a maximum power conversion efficiency of 14.6% was obtained at a bias current of 1.2 mA. These efficiencies are record high values among those reported for membrane DFB and DR lasers.

Fig. 3 shows the lasing spectrum of the membrane DR laser at a bias current of 2.6 mA, where a single mode operation with a side-mode suppression-ratio (SMSR) of 38dB was obtained. The index-coupling coefficient of the DBR was estimated to be around 800 cm^{-1} from the stop-band width of 18 nm.

IV. Conclusion

A high efficiency membrane DR laser was realized by adopting gratings with a slightly low index-coupling coefficient as well as reducing the series resistance. As a result, a record high differential quantum efficiency of 36% and also a record high power conversion efficiency of 14.6%, both for the front-side output, were obtained.

Acknowledgment

The authors would like to thank Professors S. Akiba, T. Mizumoto, M. Asada, Y. Miyamoto, and M. Watanabe of Tokyo Institute of Technology for their fruitful discussions.

References

[1] D. A. B. Miller, “Rationale and challenges for optical interconnects to electronic chips,” *Proc. IEEE*, vol. 88, no. 6, pp. 728-749, June 2000.

[2] P. Kapur, J. P. McVittie, and K. C. Saraswat, “Technology and reliability constrained future copper interconnects-Part I: Resistance modeling,” *Trans. Electron Devices*, vol. 49, no. 4, pp. 590-597, Apr. 2002.

[3] P. Kapur, G. Chandra, J. P. McVittie, and K. C. Saraswat, “Technology and reliability constrained future copper interconnects-Part II: Performance implications,” *Trans. Electron Devices*, vol. 49, no. 4, pp. 598-604, Apr. 2002.

[4] D. A. B. Miller, “Device requirements of optical interconnects to silicon chips,” *Proc IEEE*, vol. 97, no. 7, pp. 1166–1185, July 2009.

[5] T. Okamoto, N. Nunoya, Y. Onodera, T. Yamazaki, S. Tamura, and S. Arai, “Optically pumped membrane BH-DFB lasers for low-threshold and single-mode operation,” *IEEE J. Select. Topics in Quantum Electron.*, vol. 9, no. 5, pp. 1361-1366 , Sept./Oct. 2003.

[6] S. Arai, N. Nishiyama, T. Maruyama, and T. Okumura, “GaInAsP/InP membrane lasers for optical interconnects,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 17, no. 5, pp. 1381–1389, Sep./Oct. 2011.

[7] D. Inoue et al., “Sub-milliampere threshold operation of butt-jointed built-in membrane DFB laser bonded on Si substrate,” *Opt. Express*, vol. 23, no. 6, pp. 7771-7778, Mar. 2015.

[8] T. Hiratani et al., ”High asymmetric light output characteristics of membrane distributed-reflector laser on Si substrate,” *2016 International Semiconductor Conference*, ThB3, Sep. 2016.

[9] D. Inoue et al., “Low-bias current 10 Gbit/s direct modulation of GaInAsP/InP membrane DFB laser on silicon,” *Opt. Express*, vol. 24, no. 16, pp. 18571-18579, Aug. 2016.

[10] T. Hiratani et al., “Energy Cost Analysis of Membrane Distributed-Reflector Lasers for On-Chip Optical Interconnects,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 21, no. 6, art. no. 1702212, Nov./Dec. 2015.