High Asymmetric Light Output Characteristics of Membrane Distributed-Reflector Laser on Si Substrate

Takuo Hiratani[1*], Daisuke Inoue[1], Takahiro Tomiyasu[1], Kai Fukuda[1],
Tomohiro Amemiya[1,2], Nobuhiko Nishiyama[1,2], and Shigehisa Arai[1,2]
[1] Department of Electrical and Electronic Engineering, [2] Institute of Innovative Research (IIR)
Tokyo Institute of Technology, 2-12-1-S9-5 O-okayama, Meguro-ku, Tokyo 152-8552, Japan
*hiratani.t.aa@m.tithech.ac.jp

Abstract: *High asymmetric light output ratio between the front and the rear of 14.5 as well as an improved differential quantum efficiency of 29% at the front was obtained for GaInAsP/InP membrane distributed-reflector laser on Si with 50 μm-long DFB and 100 μm-long DBR sections.*
Keywords: *Semiconductor laser, Membrane laser, Distributed-reflector laser*

1. Introduction

Electrical interconnects inside LSI chips have problems such as RC delay, Joule heating, and large power dissipation [1] which will limit the performance of LSI in near future as the half-pitch scaling progresses. In order to overcome these problems, the introduction of optical interconnects to LSI is being widely studied [2], and high-speed and ultra-low power consumption logic data transmission is expected. In the on-chip optical link, light sources with ultra-low power consumption are strongly required. The membrane DFB laser, which consists thin semiconductor layers sandwiched by dielectric and air cladding layers, with high index-coupling coefficient is suitable for this purpose. Although we demonstrated low threshold current and high-speed membrane DFB lasers [3, 4], they had a problem that the external differential quantum efficiency at the front output was rather low (around 10% or lower for the front side output). To improve the light output efficiency, we introduced the distributed-reflector (DR) structure [5] to membrane lasers, and demonstrated an asymmetric light output characteristic with the ratio of 6.7 [6]. However, the external differential quantum efficiency was only 11% which was not enough compare with theoretical one. In this paper, high light output efficiency operation of membrane DR laser is demonstrated. As a result, single mode operation with a sub-mode suppression-ratio (SMSR) of 38 dB was obtained for 30 μm-long DFB section device, and an high asymmetric ratio of 14.5 as well as an external differential quantum efficiency of 29% at the front output was obtained for 50 μm-long DFB section device.

2. Device structure and Fabrication

Figure 1 shows the schematic structure of a membrane DR laser which consists of an active DFB section and a passive DBR section so as to concentrate the output in the front side. For fabrication, the initial wafer consisted of GaInAsP strain-compensated five quantum-wells and etch stop layers was prepared by gas source MBE. First, three step regrowth by OMVPE made GaInAsP waveguide section and lateral current injection structure. After deposition of SiO_2 cladding layer, the wafer was bonded to Si substrate upside down by BCB. Then, the InP substrate side and the etch stop layers were removed and electrodes were formed by evaporating Au/Zn/Au/Ti/Au and Ti/Au for p and n electrodes, respectively. Finally, the gratings at DFB and DBR sections were formed by electron beam lithography and wet chemical etching.

3. Measurement results and Discussion

Figure 2 shows the light output and current-voltage characteristics of the fabricated membrane DR laser under a room-temperature continuous-wave (RT-CW) condition. The device with the stripe width W_s of 1 μm, the DFB and DBR

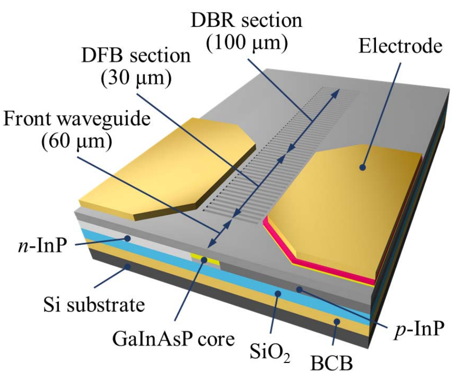

Fig. 1 Schematic of membrane DR laser.

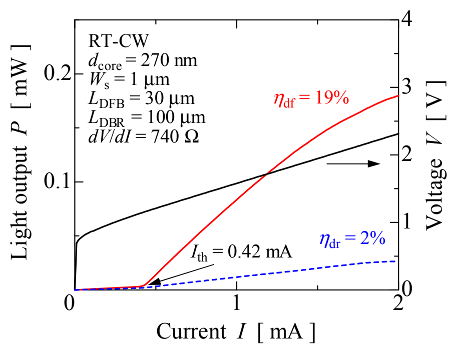

Fig. 2 Light output characteristics of membrane DR laser with DFB section length of 30 μm.

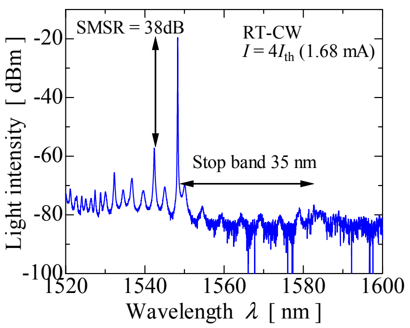

Fig. 3 Lasing spectrum of membrane DR laser.

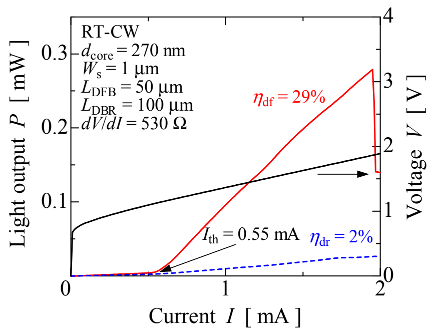

Fig. 4 Light output characteristics of membrane DR laser with DFB section length of 50 μm.

section lengths of L_{DFB} = 30 μm and L_{DBR} = 100 μm was used for the measurement. The grating period was set to 296 nm in both DFB and DBR sections. The facets of the device were formed by cleaving the waveguide section without any coating. As a result, a threshold current I_{th} of 0.42 mA (corresponding threshold current density is 1.4 kA/cm^2), an external differential quantum efficiency from front facet of 19% and a light output ratio between front and rear facet of 9.5 were obtained. The lasing spectrum is shown in Fig. 3. Single mode operation with a lasing wavelength of 1548 nm and a SMSR of 38 dB was observed at $I = 4I_{th}$. The index-coupling coefficient κ_i was estimated to be 1600 cm^{-1} from the stopband width of 35 nm. In the spectrum, the resonant mode spacing of approximately 5 nm, which corresponds to Fabry-Perot (FP) resonance inside 60 μm-long front waveguide, was observed inside the stop band. Further, Fig. 4 shows the light output characteristics of the device with 50 μm-long DFB section fabricated on the same wafer. This device shows high efficiency operation with the external differential quantum efficiency from front facet of 29%, and the light output ratio of 14.5. However, a kink is observed at a bias current of around 2 mA. The reason for the kink characteristic is mode-hopping due to existing of FP resonance, and lasing spectrum showed multimode operation. This can be solved by suppressing the facet reflection.

In this work, the fabricated devices showed 2 or 3 times higher efficiency than that of our previous work [6]. There is a possible approach to improve the external quantum efficiency. It is adjustment of the periods of DFB and DBR section. In the previous work, the mismatch between the lasing wavelength and the Bragg wavelength of DBR was concerned. Although this work showed the around 30% external differential quantum efficiency, this value is half of the theoretical value. There is a possibility that this difference comes from the low internal quantum efficiency due to leakage current at the passive waveguide section.

4. Conclusion

The membrane DR laser was fabricated in order to obtain high output efficiency with low threshold current. In the device with 30 μm-long DFB section, single mode operation with SMSR of 38 dB was shown. The device with 50 μm-long DFB section showed high external differential quantum efficiency from front facet of 29%. These results show that the membrane DR laser is suitable for on-chip light source in terms of low power consumption and high light output efficiency.

Acknowledgment

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References

[1] 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.

[2] D. A. B. Miller, "Rationale and challenges for optical interconnects to electronic chips," Proc. IEEE, vol. 88, no. 6, pp. 728–749, June 2000.

[3] D. Inoue, J. Lee, T. Hiratani, Y. Atsuji, T. Amemiya, N. Nishiyama, and S. Arai, "Sub-milliampere threshold operation of butt-jointed built-in membrane DFB laser bonded on Si substrate," Opt. Exp., vol. 23, no. 6, pp. 7771–7778, Mar. 2015.

[4] D. Inoue, T. Hiratani, K. Fukuda, T. Tomiyasu, T. Amemiya, N. Nishiyama, and S. Arai, "High-modulation efficiency operation of GaInAsP/InP membrane distributed feedback laser on Si substrate," Opt. Exp., vol. 23, no. 22, pp. 29024–29031, Oct. 2015.

[5] K. Ohira, T. Murayama, S. Tamura, and S. Arai, "Low-threshold and high efficiency operation of distributed reflector lasers with width-modulated wirelike active region," IEEE J. Sel. Topics Quantum Electron., vol. 11, no. 5, pp. 1162–1168, Sep./Oct. 2013.

[6] T. Hiratani, D. Inoue, T. Tomiyasu, Y. Atsuji, K. Fukuda, T. Amemiya, N. Nishiyama, and S. Arai, "Room-temperature continuous-wave operation of membrane distributed-reflector laser," Appl. Phys. Exp., vol. 8, no. 11, 112701, Oct. 2015.