High Efficiency and High-speed Modulation Characteristics of Membrane Distributed-Reflector Laser on Si

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For the realization of on-chip optical interconnection, an ultra-low power consumption semiconductor laser, which can be operated with low drive current (< 1 mA) and high-speed (>10 Gbit/s) direct modulation, is strongly needed. Thus, to meet these demands, we proposed and demonstrated membrane DFB and distributed-reflector (DR) lasers [1, 2]. In this work, we report the membrane DR laser which exhibited a record high efficiency as well as a record high-speed modulation among membrane-based DFB and DR lasers.

Figure 1 (a) shows the structure of fabricated membrane DR laser on Si bonded by BCB. Although this device was fabricated using the same initial wafer, which had five GaInAsP quantum well with total thickness of 270 nm, in our previous work [2], several improvements have been made to obtain high efficiency operation. The doping concentration of the regrown *p*-InP side cladding layer was reduced from 2×10^{18} cm^{-3} to 5×10^{17} cm^{-3} for the reduction of the optical absorption loss. In order to compensate the increase of series resistance due to the adoption of low doped *p*-InP side cladding layer, the distance W between the *p*-side electrode and the active section was reduced from 3 μm to 1.6 μm as shown in Fig. 1 (b).

Figure 2 shows the current-light and voltage-current characteristics of the fabricated device. The DFB and DBR section lengths and the stripe width W_s were 32 μm, 50 μm, and 0.8 μm, respectively. A threshold current I_{th} of 0.21 mA (threshold current density J_{th} of 820 A/cm^2) and an external differential quantum efficiency η_{df} of 32% (front side output) were obtained. This η_{df} was a record high value among membrane DFB and DR lasers ever reported. The power conversion efficiency of the device is also shown in Fig. 3. Although a maximum power conversion efficiency η_{PCmax} of 12% was obtained at a bias current of 0.64 mA, η_{PCmax} can be improved to approximately 30% by reducing the distance W to 0.8 μm and introducing membrane photonic-integrated-circuit.

Next, the direct modulation response of this device was measured. As can be seen in Fig. 4, which depicts the 3dB bandwidth and relaxation oscillation frequency obtained from small signal modulation response, the slopes of f_{3dB} and f_r (modulation current efficiency factor) were 15 GHz/mA$^{1/2}$ and 12 GHz/mA$^{1/2}$, respectively. This f_r is also a record higher value than that reported in the previous work [1]. In addition, 15 Gbit/s large signal modulation was measured by using an Er-doped fiber amplifier (EDFA) and a tunable bandpass filter. Although it shows slight error-floor, a bit-error-rate (BER) of 5.7×10^{-13} was obtained, as shown in Fig. 5, for NRZ signal modulation (PRBS 2^{31}-1) at average received power of -0.4 dBm when the bias current and modulation voltage were set to be 1.08 mA and 0.522 V_{pp}.

References

[1] D. Inoue *et al.*, "Low-bias current 10 Gbit/s direct modulation of GaInAsP/InP membrane DFB laser on silicon," *Optics Express*, vol. 24, no. 16, pp. 18571–18579, May/July 2016.

[2] T. Hiratani *et al.*, "90°C continuous-wave operation of GaInAsP/InP membrane distributed-reflector laser on Si substrate," *Appl. Phys. Express*, vol. 10, no. 3, pp. 032702, Jan./Feb. 2017.

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Figures

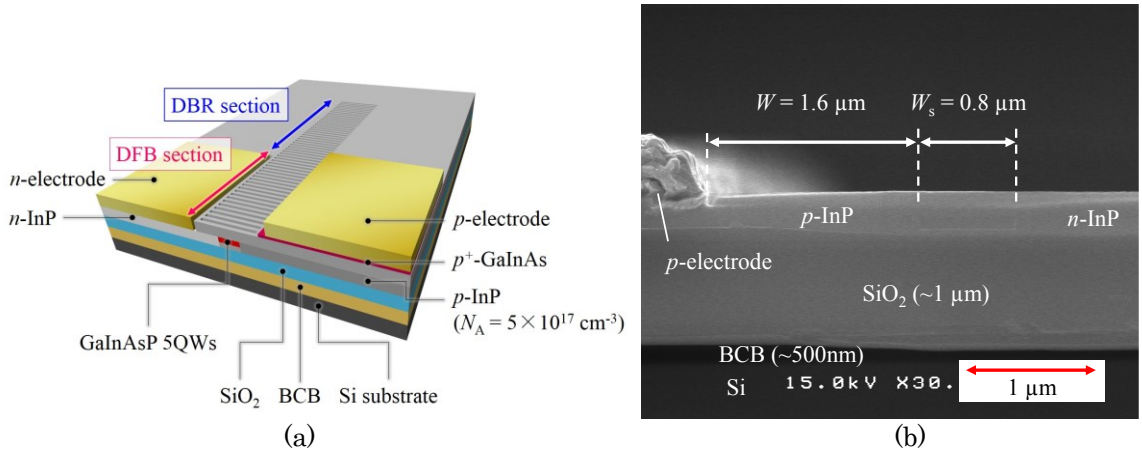

Fig. 1. (a) Schematic of membrane DR laser (b) Cross-sectional SEM view of the fabricated device.

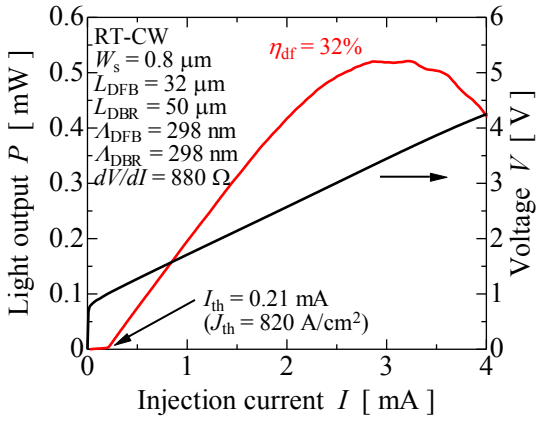

Fig. 2. Current–light output and current–voltage characteristics of membrane DR laser.

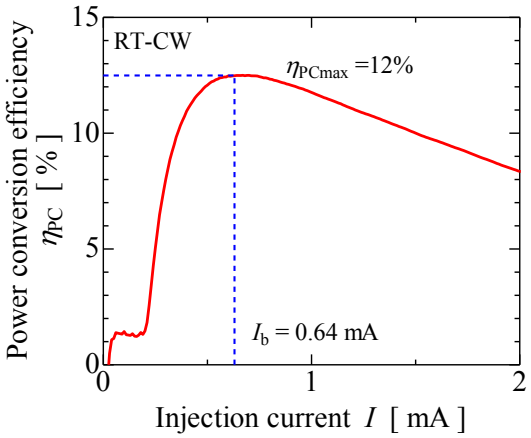

Fig. 3. Power conversion efficiency of membrane DR laser.

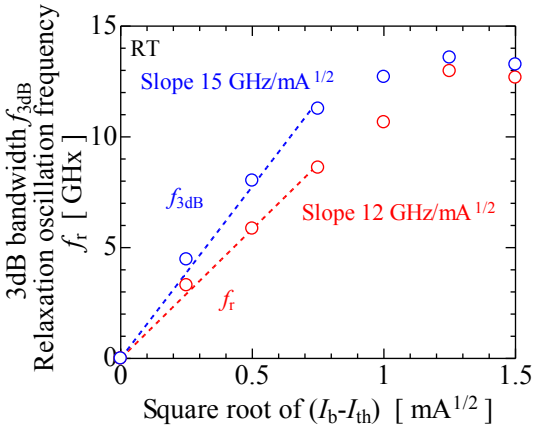

Fig. 4. 3dB bandwidth and relaxation oscillation frequency obtained from small signal modulation response.

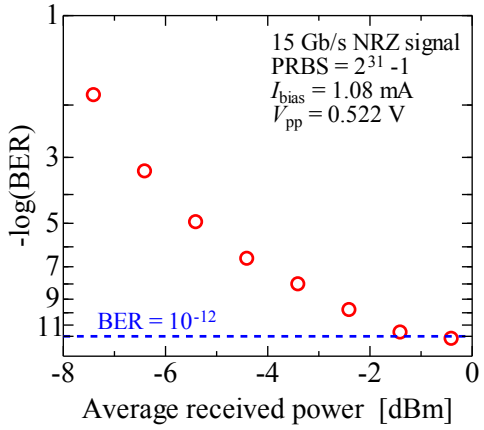

Fig. 5. 15 Gbit/s BER characteristics.