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Low-Power and High-Speed Operation Capabilities of Semiconductor Membrane Lasers – Energy Cost Limited by Joule Heat

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***Short-Abstract*—The power consumption of a lateral current injection (LCI) type membrane distributed reflector (DR) laser under a high-speed direct modulation was theoretically investigated. As the results, we found that there is an optimal cavity length, which can be determined by the series resistance, to minimize the power consumption. For an example, an energy cost of 37 fJ/bit can be obtained at a modulation speed of 10 Gb/s for the cavity length of 17 µm when the grating coupling coefficient of 1800 cm^{-1} and the resistivity of *p*-InP cladding layer of 0.035 Ω·cm are used.**

I. INTRODUCTION

Optical interconnects provide significant performance improvement and power savings over copper-based solutions in conventional large-scale integrated circuits (LSIs) [1]. Here in the case of global on-chip wiring, we should aim at targeted energy of ~100fJ/bit [2]. For this purpose, on-chip light sources with low power consumption, such as VCSELs [3] and photonic crystal lasers [4, 5], have been reported in recent years. In particular, the ultra-low energy operation of 4.4 fJ/bit was demonstrated in a system combining the photonic crystal laser and an avalanche photo diode (APD) [6]. However, in the receiver side, the use of PIN photodiodes instead of APDs is recommended from the viewpoint of a total system power consumption. Therefore, it is strongly desired to realize on-chip lasers with low power consumption and with sufficient output power for error-free operations using a PIN photodiode.

Toward the above target, we have proposed a semiconductor membrane laser [7] and demonstrated room-temperature continuous-wave (RT-CW) operation under current injection [8]. The membrane structure consists of a thin semiconductor core layer sandwiched by much lower refractive-index materials such as SiO_2, BCB, and air. This high index-contrast structure enables to realize strong optical confinement into the active region, and results in low threshold current operation. Further, we can control the light output by introducing the grating structure in the semiconductor membrane laser.

In this work, we show fundamental performance of a membrane distributed-reflector (DR) laser for low power consumption operation under a high-speed direct modulation condition. Moreover the cavity length dependence of energy cost for 10 Gb/s data transmission is theoretically given by taking into account the Joule heat in the series resistance. As the result, it is shown that the increase of power consumption in the Joule heat limits the low power consumption operation.

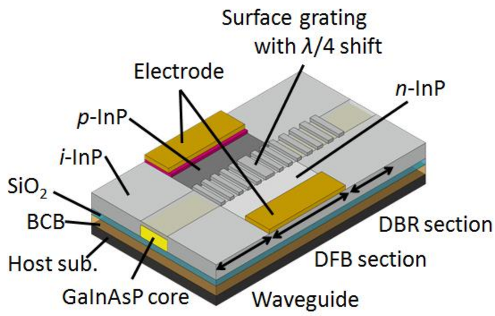

Fig. 1 Schematic view of a LCI membrane DR laser

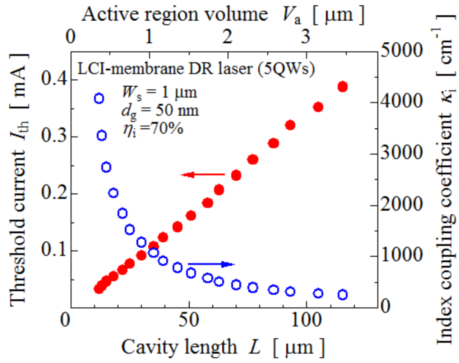

Fig. 2 Cavity length dependence of threshold current I_{th} for various index coupling coefficients.

II. ANALYSIS OF SEMICONDUCTOR MEMBRANE DR LASER

The structure of a lateral current injection type membrane-DR (LCIM-DR) laser is shown in Fig. 1. The DR structure consists of DFB section including active layer and distributed-Bragg-reflector (DBR) section [9]. In the calculation, we assumed a DBR with the reflectivity of 99% at the one side of the laser cavity, and introduced $\lambda/4$ phase-shift in the DFB section to reduce the threshold current.

As analysis of the performances, we calculated the minimum threshold current for a given index-coupling coefficient κ_i of the LCIM-DR laser with surface grating structure as shown in Fig. 2. The index-coupling coefficient κ_i was determined by varying core thickness with a fixed grating depth d_g = 50 nm. The stripe width W_s and the internal

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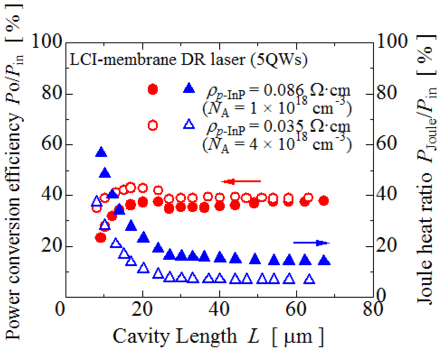

Fig. 4 Power conversion efficiency and Joule heat ratio for different resistivities.

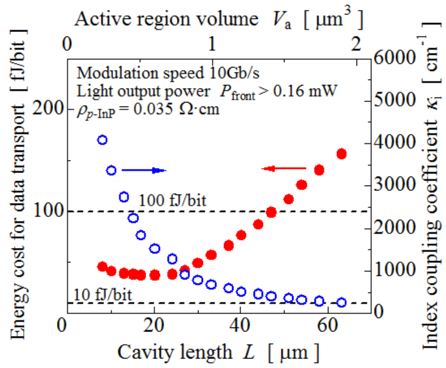

Fig. 5 Cavity length dependence of energy cost for various index coupling coefficients.

quantum efficiency η_i were assumed to 1 μm and 70%, respectively. As can be seen, the threshold current decreases with a decrease of the cavity length, and a threshold current of 32 μA can be obtained for a cavity length of 10 μm and κ_i of 4000 cm^{-1} (d_{core} = 150 nm). This result simply shows that a shorter cavity with high index-coupling coefficient is required for ultralow threshold current operation.

III. Power Consumption and Joule Heat

An ultra-low energy cost of less than 100 fJ/bit is required for the light source for on-chip optical interconnection as mentioned previously. Furthermore, there is a requirement for light output determined by the minimum receivable power of a photo-detector and a link loss including coupling loss between each device and waveguide loss. We used the minimum receivable power of -13 dBm (0.05 mW) which is usually used for an average performance GaInAs *p-i-n* photodiode (PIN-PD) at 10 Gb/s operation and the link loss was assumed to be 5 dB, hence the required light output was estimated to be -8 dBm (0.16 mW) for a 10 Gb/s transmission.

For estimation of total power consumption of the LCIM-DR laser, we assumed *p*-InP cladding layer resistance as the device resistance because it is dominant in the total resistance. Fig. 4 shows cavity length dependences of the power conversion efficiency and Joule heat ratio of the LCIM-DR laser. In the case of *p*-InP cladding layer resistivity of $\rho_{p\text{-InP}}$= 0.086 Ω·cm (the doping concentration of N_A = 1 × 10^{18}/cm^3) calculated from *p*-InP mobility [10], the Joule heat is remarkable for the cavity length of less than 20 μm. However, it can be reduced to less than half by increasing N_A to 4 × 10^{18}/cm^3 ($\rho_{p\text{-InP}}$= 0.035 Ω·cm), and it will suppress the drastic decrease of power conversion efficiency in very short cavity length range.

Finally, we estimated an energy cost for 10 Gb/s data transmission for various cavity lengths (and κ_i) as shown in Fig. 5. As can be seen, the energy cost of less than 100 fJ/bit can be obtained with the cavity length of less than 50 μm, and the minimum energy cost of 37 fJ/bit can be obtained for the cavity length of 17 μm (κ_i =1800 cm^{-1}).

IV. Conclusion

We theoretically investigated the operation energy of LCIM-DR lasers for low-power and high-speed operation. The threshold current of 32 μA can be obtained by shortening the cavity length to 10 μm, however, there is an optimal cavity length to minimize the energy cost, and the minimum energy cost of 37 fJ/bit can be obtained with the cavity length of 17 μm. This means that the power consumption is limited by Joule heat in short cavity length lasers.

Acknowledgment

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