Low-Power-Consumption High-Eye-Margin 10-Gb/s Operation by GaInAsP/InP Distributed Reflector Lasers With Wirelike Active Regions

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***Abstract*—Low-driving-current and high-eye-margin 10-Gb/s operation was demonstrated by a GaInAsP/InP distributed reflector (DR) laser with wirelike active regions. The reduction of modulation bias currents was realized by the high modulation efficiency of five-stack quantum wirelike active regions as well as thin optical confinement layers for a shorter carrier transit time. A mask test of 10 GbE with 20% margin was passed with a low bias current of 10 mA, and the maximum 3-dB bandwidth was over 15 GHz.**

***Index Terms*—Distributed reflector (DR) laser, high-speed modulation, low-power consumption, semiconductor lasers.**

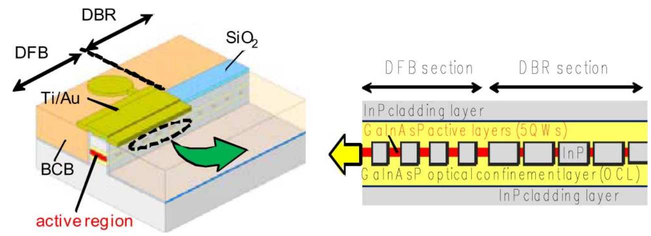

Fig. 1. Schematic and cross-sectional structures of DR laser with wirelike active regions.

I. Introduction

THE demand for low-power consumption, high-speed optical transmitters has soared in order to deal with the explosive growth of data transmission. In particular, to access network systems and optical local area networks (LANs), increasing power consumption and the cost of high modulation speed have become critical issues. Moreover, the market for active optical cables replacing offline electronic interconnects is growing rapidly; therefore, developing a cost-effective and low-power-consumption light source is essential. Hence, semiconductor lasers with an ultralow threshold current have been widely reported in terms of production cost and power consumption. Vertical-cavity surface-emitting lasers (VCSELs) [1]–[3] and distributed feedback (DFB) lasers with high index-coupling coefficients [4], [5] have demonstrated low-threshold-current operation in the sub-mA range. Microdisk and photonic crystal lasers [6], [7] have also demonstrated ultralow threshold current properties, whereas their light outputs were not practical for optical fiber applications.

A distributed reflector (DR) laser consisting of distributed feedback (DFB) and distributed Bragg reflector (DBR) sections with wirelike active regions [8] shown in Fig. 1 can also be operated with a low threshold current because of its small active volume and strong index-coupling owing to its structural features. High performance of DR lasers, for instance, sub-mA threshold current and high efficiency of approximately 50%, was successfully reported [9]. The term "wirelike" was introduced in order to distinguish the strongly index-coupled gratings with spatially separated active regions from low-dimensional quantum-wire structures. In terms of dynamic characteristics of DR lasers, superior properties such as modulation sensitivity and spectral chirping were theoretically predicted [10]. Moreover, preliminary data transmission experiments of 5 Gb/s-10 km and 10 Gb/s-10 km were reported [11]. However, 3 dB bandwidth was limited to less than 10 GHz, which may be attributed to a smaller modal gain and a shorter carrier transit time from the optical confinement layers (OCLs) to the wirelike active regions.

In this letter, we report the high-speed operation of DR lasers by increasing the number of quantum wells (QWs) and reducing the carrier transit time in the OCLs. Successful 10 Gb/s operation with 20% mask margin was obtained with a low bias current of 10 mA and a small voltage swing of $0.53V_{p\text{-}p}$. The record-high modulation efficiency of 3.0 $\text{GHz/mA}^{0.5}$ for GaInAsP quantum-well lasers was also achieved.

II. Device Structure

Since the modulation bandwidth of directly modulated lasers is proportional to the relaxation oscillation frequency (f_r), the

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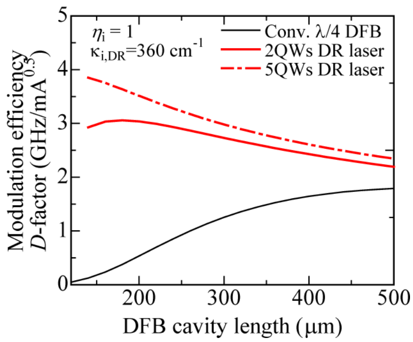

Fig. 2. Calculated D-factors as a function of DFB cavity length. The width of the wirelike active region is assumed to be 90 nm in the period of 240 nm for DR lasers, while the conventional $\lambda/4$ phase-shifted DFB laser is assumed to be consisting of 2QWs.

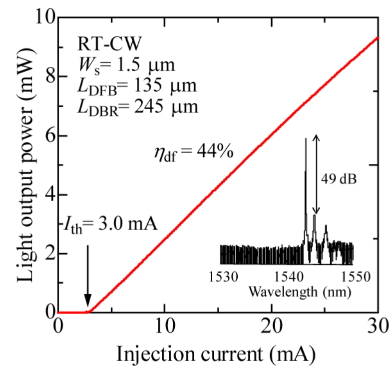

Fig. 3. Injection current–light output power (I–L) characteristic and lasing spectrum at $2I_{\rm th}$ (inset).

slope of f_r with respect to the bias currents, which is called the modulation efficiency D-factor, should be high for both high-speed and low-power-consumption operations. The D-factor can be approximately given by

$$D\text{-factor} \equiv \frac{f_r}{\sqrt{I - I_{\rm th}}} = \frac{1}{2\pi}\sqrt{\frac{\eta_i}{q}\frac{\xi_w \xi_L}{V_a}G'}, \qquad (1)$$

where η_i is the internal quantum efficiency, q the unit charge, ξ_w the vertical optical confinement factor per well ($= 1\%$), ξ_L the longitudinal optical confinement factor, V_a the active volume, and G' the differential optical gain. Because the active regions are distributed along the laser cavity, ξ_L must be taken into account for the structure with wirelike active regions. Since DR lasers have a high index-coupling coefficient greater than 300 cm^{-1}, short-cavity lasers can be realized. Moreover, the widths of wirelike active regions are typically less than half the grating period, whereas ξ_L is maintained at approximately 70% due to the gain matching effect [8]. For these reasons, the optical confinement per unit volume of DR lasers is higher than that of conventional DFB lasers; thus, a high D-factor can be expected for DR lasers. It is worth mentioning that the excess nonradiative recombination for wirelike structures was found to be less than 10% by comparison between the DFB lasers with wirelike active regions and FP lasers with quantum-well active regions. Fig. 2 shows the calculated D-factor as a function of DFB cavity length. The index-coupling coefficients of 360 cm^{-1} and 50 cm^{-1} were used for the wirelike DFB section and the conventional $\lambda/4$ phase-shifted DFB laser, respectively. As can be seen, a high D-factor over 3 GHz/mA$^{0.5}$ can be easily achieved for DR lasers with wirelike active regions.

The fabricated DR laser has a 1.5-μm-wide high-mesa stripe geometry surrounded by benzocyclobutene (BCB) and consists of an active DFB section with wirelike active regions and a passive DBR section as shown in Fig. 1. The designed wire widths of the DFB and DBR sections were 115 and 80 nm in the periods of 242.50 and 243.75 nm, respectively. Since the lasing wavelength of DFB section with wirelike active regions is always on the long wavelength side of the stopband, the grating period in the DBR section was longer than that in the DFB section so as to match the Bragg wavelength in the DBR section with the lasing wavelength. The monolithic integration of the DBR section which replaces an HR coating leads to simple fabrication process, particularly in the case of short-cavity (<100 μm) DFB lasers for low threshold current operation. While the previously reported DR lasers [9] utilized 2QWs for low-threshold-current operations, the 5QWs structure (a combination of a 6-nm-thick $Ga_{0.22}In_{0.78}As_{0.81}P_{0.19}$ quantum-well layer and a 10-nn-thick tensile-strained $Ga_{0.25}In_{0.75}As_{0.50}P_{0.50}$ barrier layer) was adopted in this work for high D-factor and modulation speed. A low dielectric-constant material of BCB was placed below the electrode pad (80 μm diameter) and thin $Ga_{0.22}In_{0.78}As_{0.47}P_{0.53}$ OCLs of 40 nm were adopted to obtain a high RC electrical bandwidth and a short carrier transit time.

III. Experimental Results and Discussion

Fig. 3 shows the current-light output $(I\text{-}L)$ characteristic of a DR laser under a room-temperature continuous-wave (RT-CW) condition. A moderately low threshold current $(I_{\rm th})$ of 3.0 mA and a high differential quantum efficiency from the front facet (η_{df}) of 44% were obtained. Since the number of quantum wells was increased from 2 to 5 for high-speed modulation, the threshold current was 2–3 times higher than that in our previous report. While both facets were just cleaved, a single-mode operation with a submode suppression ratio (SMSR) of 49 dB at a bias current of $2I_{\rm th}$ was achieved as shown in the inset of Fig. 3. This confirms single-mode operation of wirelike active regions due to the gain matching effect [8].

Measurement results of the small signal response S_{21} and modulation efficiency are shown in Figs. 4 and 5, respectively. f_r measured from the relative intensity noise (RIN) yields a modulation efficiency D-factor of 3.0 GHz/mA$^{0.5}$, which is, to the best of our knowledge, the highest value for GaInAsP DFB lasers and comparable to that of state-of-art AlGaInAs quantum-well lasers [12], [13]. The slight decrease of D-factor along with the current injection may be attributed to the reduced effective current into the active regions caused by the frequency characteristics of the residual RC parasitics and a submount. The small signal 3 dB bandwidth of 15 GHz was obtained at a bias current of 28 mA.

Fig. 6(a) shows the measured eye diagram carried out with $2^{31} - 1$ pseudorandom bit sequence (PRBS) data streams for nonreturn-to-zero (NRZ) signals. The DFB section was biased with 10 mA at the bit rate of 10.3125 Gb/s. The peak-to-peak

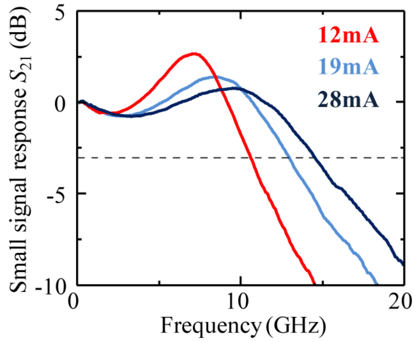

Fig. 4. Small signal characteristic at various bias currents.

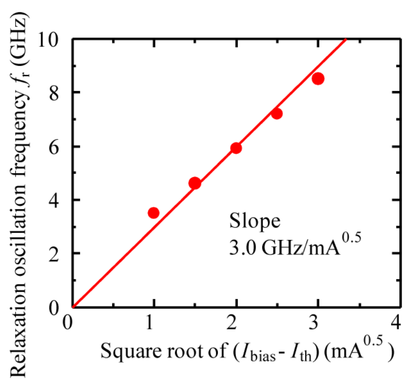

Fig. 5. Measured modulation efficiency from RIN spectrum.

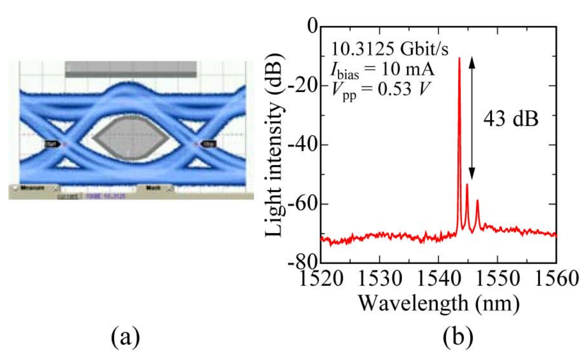

Fig. 6. (a) Eye pattern and (b) optical spectrum under 10.3125-Gb/s modulation.

modulation voltage swing was as low as 0.53 V, which achieved the extinction ratio of 6 dB at 20°C. This level of driving electricity can be supplied using low-cost modulation drivers manufactured by standard CMOS process such as a VCSEL-driver chip, although this laser is an edge-emitting-type laser. Also, a stable single-mode operation with a SMSR of 43 dB under 10.3125 Gb/s modulation is shown in Fig. 6(b).

IV. Conclusion

We successfully demonstrated the low-power-consumption and high-eye-margin 10 Gb/s operation of a DR laser with wirelike active regions. By introducing five-stack quantum wirelike active regions with thin optical confinement layers, the reduction of modulation bias currents and high bandwidth were realized. Experimentally, the advantage of wirelike structures in terms of high modulation efficiency was demonstrated with a record-high D-factor of 3.0 GHz/mA$^{0.5}$ for GaInAsP DFB lasers. A mask test of 10 GbE with 20% margin was passed with a low bias current of 10 mA and modulation voltage of $0.53V_{p-p}$; thus, DR lasers can be operated using low-cost modulation driving circuits. Therefore, the DR laser with wirelike active regions is promising for low-power-consumption, low-cost light sources for high-speed access networks and optical interconnects.

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