Low-power Consumption and High-eye-margin 10 Gbit/s Operation of Distributed Reflector Laser with Wirelike Active Regions

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ABSTRACT

By introducing 5-quantum-well wirelike active regions with thin optical confinement layers, low-power and high-speed operation of GaInAsP/InP distributed reflector (DR) laser with wirelike active regions was realized. A mask test of 10 GbE with a 20% margin was passed with a low bias current of 10 mA and the 3 dB bandwidth of 15 GHz was obtained with the bias current of 28 mA.

I. INTRODUCTION

The demand for high bit-rate access networks grows rapidly due to the explosive growth of data transmission. In order to deal with increasing data capacity and power consumption in access network applications and optical interconnections, single-mode lasers capable of high-speed modulation with low power-consumption are strongly demanded.

Although semiconductor lasers integrated with electro-absorption modulators [1] could be used for 25 Gbps or 40 Gbps operation, there is no doubt that the direct modulation of semiconductor lasers is, we believe, the best solution because of its simplicity and low drive voltage [2]. A distributed reflector (DR) laser, consisting of distributed feedback (DFB) and distributed Bragg reflector (DBR) sections, is a good candidate for such applications since a stable single-mode operation with high output efficiency from one side facet can be attained and superior properties such as modulation sensitivity and spectral chirping were also theoretically predicted [3]. Recently, DR lasers with GaInAsP-multiple-quantum-well (MQW) wire-like active regions, such as indicated by Fig. 1, have been demonstrated with a low threshold current and stable single-mode property because of its small active volume and strong index-coupling grating structure [4]. For an example, a superior operation with sub-mA threshold current as well as high differential quantum efficiency of approximately 50% from the front facet was achieved [5,6]. However, its 3 dB bandwidth was limited to less than 10 GHz although data transmission experiments of 5 Gbps-10 km and 10 Gbps-10 km were reported [7].

In this paper, we reveal the limiting factor for high speed modulation of DR lasers with wirelilke active regions and demonstrate a successful 10 Gbit/s operation with low-power consumption and high-eye-margin. After description of the difference of the carrier transport effect between wirelike active regions and conventional QW active regions, experimental results of static and dynamic characteristics, will be reported.

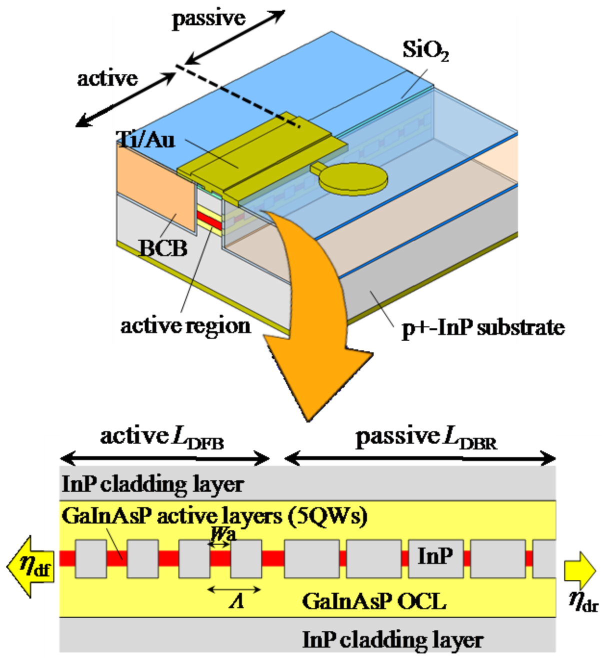

Fig. 1 Schematic and cross-sectional structures of DR laser with wirelike active regions.

II. CARRIER TRANSPORT IN WIRELIKE ACTIVE REGIONS

Figure 2(a) shows the typical separate-confinement hetero-structure (SCH) consisting of QW active regions sandwiched by optical confinement layers (OCLs). It is known that the carrier transport effect in the OCLs restricts the modulation bandwidth [8] and this is mainly governed by the classical current continuity equations which describe the diffusion, recombination, and drift of carriers across the SCH in the presence of any electric

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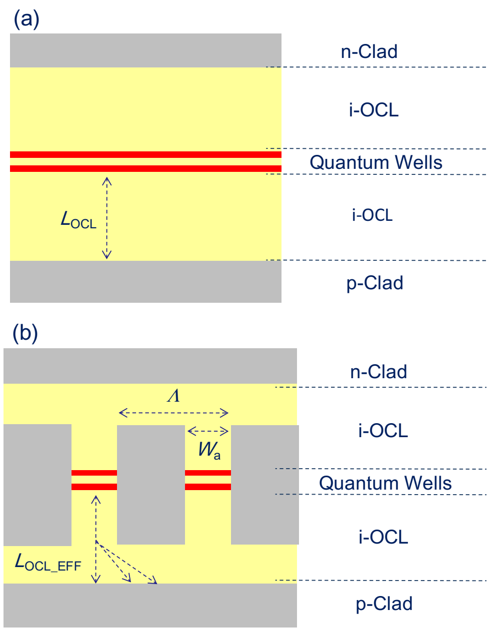

Fig. 2 Cross-sectional structures of (a) quantum-well and (b) wirelike active regions.

field. Eq. (1) shows the transport time t_{ocl} and 3dB frequency f_{3dB} from the current continuity equations [8]

$$\tau_{OCL} = \frac{L_{OCL}^{2}}{2D_a}, \qquad f_{3dB} = \frac{1}{2\pi\tau_{OCL}} = \frac{2D_a}{2\pi L_{OCL}^{2}}, \tag{1}$$

where L_{OCL} is the thickness of GaInAsP optical confinement layer (OCL) and $D_a = 2D_n D_h/(D_n + D_h)$ is an ambipolar diffusion coefficient (D_n and D_h mean the diffusion coefficients of electrons and holes, respectively). It is known that 3dB bandwidth is inversely proportional to square of L_{OCL} and sensitive to the thickness of OCL.

As can be seen in Fig. 2(b), carriers in the OCL below the groove embedded with InP transport longer distance than L_{OCL}, hence an effective length, L_{OCL_EFF} should be considered for DFB or DR lasers with wirelike active regions. However analytical expression of L_{OCL_EFF} is difficult, we estimated the modulation bandwidth dependence of wirelike active regions by numerical calculation using the two-dimensional diffusion equation and discretized it by forward-time centered- space (FTCS) method. The two-dimensional diffusion equation is expressed by,

$$\frac{\partial T(x,y,t)}{\partial t} = D_h \frac{\partial^2 T(x,y,t)}{\partial x^2} + D_h \frac{\partial^2 T(x,y,t)}{\partial y^2} \tag{2}$$

where $T(x,y,t)$ is the carrier density at position (x, y) and time t. We calculated the diffusion of holes because the limitation of diffusion is dominated by holes due to the much smaller mobility of holes compared to that of electrons.

Figure 3 shows the calculated 3dB bandwidth dependence on the OCL thickness for various wire widths.

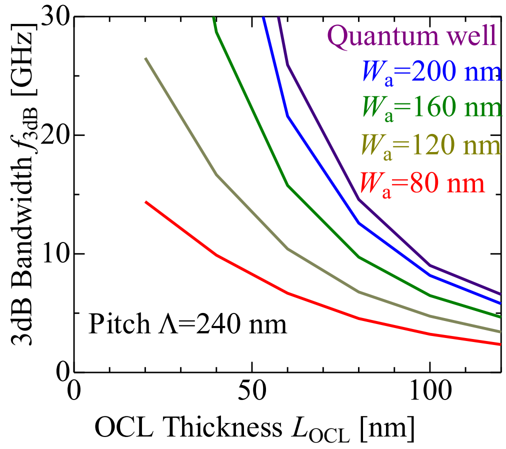

Fig. 3 3dB bandwidth dependence on various wire widths.

As can be seen, the 3dB bandwidth of DFB/DR lasers with wirelike active regions is lower than that of QWs, and the narrower the wire width becomes, the smaller the 3dB bandwidth is. Therefore, introducing thinner OCL thickness with the consideration of the balance of optical confinement factor and carrier transport is very important to achieve high speed and low power consumption DR lasers with wirelike active regions.

III. Experimental Results and Disucussion

According to the calculated results, we designed DR lasers with thin OCLs of 40nm for the active region wire width of the DFB section of 120 nm to enable the 3dB bandwidth of around 15 GHz. With this OCL thickness, the optical confinement factor was 0.95%/well, which is slightly lower than our previous structure (1.1%/well). Fabricated DR laser had the wirelike active region width of 115 and 80 nm in the periods of 242.50 and 243.75 nm, respectively, for the DFB and the DBR sections. In addition to this, an initial wafer of 5 QWs was used for high D-factor and modulation speed in this work while the previously reported DR lasers utilized 2QWs for low-threshold-current operations [5]. A low dielectric-constant material of Benzocyclobutene (BCB) was placed below the electrode pad (80 μm diameter) so as to obtain a high bandwidth limited by parasitic constant.

Figure 4 shows the current-light output *(I-L)* characteristic of the fabricated DR laser with uniform grating structure. Both facets were just cleaved and no facet coating was carried out. Under a room temperature continuous-wave (RT-CW) condition, a threshold current (I_{th}) of 3.0 mA and a high differential quantum efficiency from the front facet (η_{df}) of 44% were obtained with the active DFB section length of 135 μm and the stripe width of 2.5 μm. Since the number of quantum wells was increased from 2 to 5 for high-speed modulation and the structure had slightly lower optical confinement factor, the threshold current was 2-3 times higher than that in our

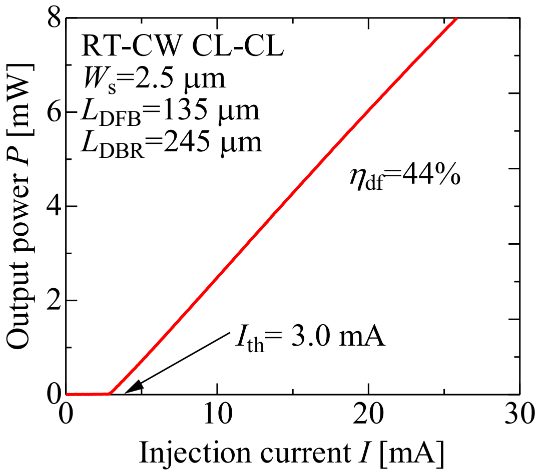

Fig. 4 Injection current-light output power (I-L) characteristic.

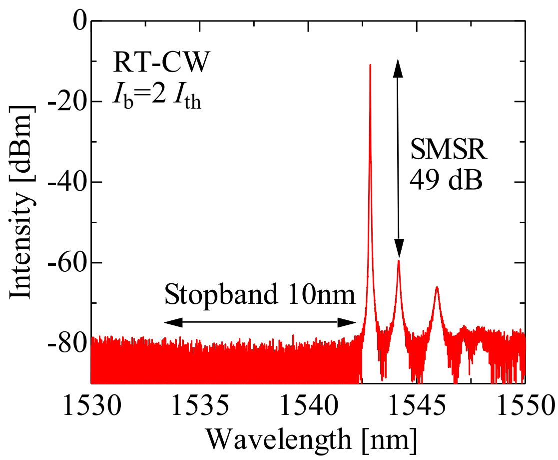

Fig. 5 Lasing spectrum at 2 times the threshold.

previous report [5]. Figure 5 shows the lasing spectrum under a RT-CW condition at a bias current of $2I_{th}$, where single-mode operation was obtained with the sub-mode suppression-ratio (SMSR) of 49 dB. Although the stopband was not clearly observed, the index-coupling coefficient of the grating was estimated to be approximately 400 cm^{-1} and the stopband was estimated to be 10 nm.

Dynamic characteristics were measured by relative intensity noise (RIN) and small-signal modulation response. Figure 6 shows the relaxation oscillation frequency f_r dependence on the square root of bias current above threshold $(I-I_{th})^{1/2}$. f_r was measured from the peak frequency of intensity-noise spectrum to avoid the influence of the RC roll-off. The slope value of this f_r was about 3.0 GHz/$mA^{1/2}$ which is very high among those reported for GaInAsP materials and is comparable to state-of-art AlGaInAs quantum-well lasers [2]. We believe this large value is attributed to the wirelike active regions because carriers are injected into almost a half of the grating period and contribute to increase the modal gain efficiently.

The small signal modulation response was measured for various bias currents as shown in Fig. 7. 3 dB frequency (f_{3dB}) increased with increasing a bias current, and 3dB bandwidth of 15 GHz was obtained at a bias current of 28 mA. This bandwidth value agrees to that estimated for the OCL thickness of 40 nm and the wirelike active region width of 120 nm as shown in Fig. 3, while previously reported DR laser with the OCL thickness of 120 nm showed the 3dB bandwidth of only 5 GHz [7]. From the results shown in Fig. 3, the 3dB bandwidth exceeding 20 GHz can be obtained by reducing the OCL thickness to 30 nm from the view point of carrier transport although we have to consider optical confinement as well to achieve high optical bandwidth.

Then we carried out large signal direct modulation experiment at 10.3125 Gbit/s with 2^{31}-1 pseudo random bit sequence (PRBS) data streams for non-return-to-zero (NRZ) signals. The device was mounted on an AlN submount with a 40 Ω impedance matching resistance.

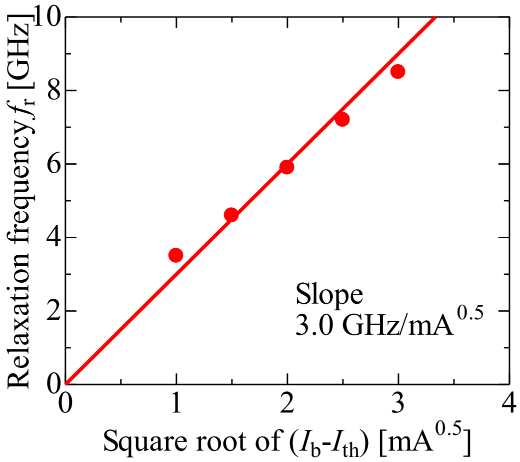

Fig. 6 Measured modulation efficiency from RIN spectrum.

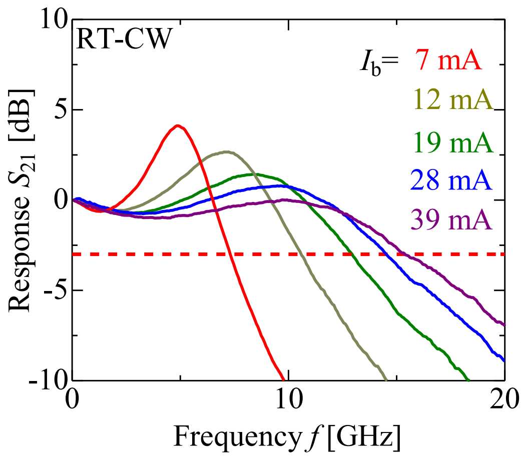

Fig. 7 Small signal characteristic with various bias currents.

Figure 8 shows the eye-pattern measured under a bias current of only 10 mA and the modulation voltage of 0.53 V_{pp} which achieved an extinction ratio of 6 dB at 20°C. As can be seen, very clear eye opening for 10GbE masktest of 20% margin was demonstrated.

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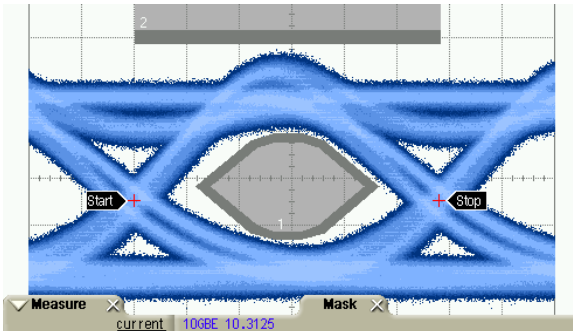

Fig. 8 10.3125 Gbit/s eye pattern with a bias current of 10 mA.

IV. Conclusion

We have revealed the unique limiting factor of DR lasers with wirelike active regions and demonstrated high-speed and low-power consumption 10 Gbit/s direct modulation. Theoretical calculation showed that the carrier transport time in the OCL beneath the embedding InP layer strongly affect to the modulation bandwidth, and indicated the necessity of thinner OCL design. By adopting thin OCLs of 40 nm and five-quantum wells for higher modulation speed, the slope value of the relaxation oscillation frequency f_r of 3.0 GHz/mA$^{0.5}$ was obtained thanks to the low-threshold current characteristics of DR lasers, and 3 dB bandwidth over 15 GHz has been achieved with relatively low bias current of 28 mA. Furthermore, a mask test of 10 GbE with 20% margin was passed with a bias current of as low as 10 mA and modulation voltage of 0.53 $V_{p\text{-}p}$. These results show that DR laser with wirelike active regions is promising as a light source for access network applications and optical interconnections.

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