1.5-\(\mu\)m and 10-Gbs\(^{-1}\) etched mesa buried heterostructure DFB-LD for datacenter networks

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Abstract

We report a 1.5\(\mu\)m and 10 Gb s\(^{-1}\) etched mesa buried heterostructure \(\lambda/4\)-shifted distributed feedback laser diode (DFB-LD) for the low-cost application of WDM-based datacenter networks. To reduce the threshold current and improve the modulation bandwidth in a conventional p-/n-/p-InP current blocking structure, a thin undoped InP (u-InP) layer was inserted between the side walls of the active region and the p-InP layer (i.e., a u-/p-/n-/p-InP structure), and the region containing the active region and the current blocking structures was etched in a mesa form (i.e., an etched mesa). From this work, it was found that a 300\(\mu\)m long anti-reflection (AR)-AR DFB-LD with a mesa width of 8\(\mu\)m is reduced by about 25% while a side mode suppression ratio is >50 dB and a 3 dB bandwidth is >10 GHz at a current of 40 mA; in addition, it shows a clear eye-opening with a dynamic extinction ratio of >4.5 dB at 10 Gb s\(^{-1}\), and a power penalty of <1 dB after a 2 km transmission.

Keywords: distributed feedback laser diode, buried heterostructure, current blocking structure

(Some figures may appear in colour only in the online journal)

1. Introduction

Directly modulated lasers (DMLs) have been employed as a light source for most commercial fiber-optic transmission systems, such as those at 2.5 Gb s\(^{-1}\) [1, 2]. The demand and areas of application of DMLs are expanding, not only in higher-bit-rate transmission systems such as 10 and 40 Gb s\(^{-1}\) systems, but also in rather short-distance fiber-optic networks utilizing a WDM. In particular, for the application of datacenter networks (e.g., a 10 \times 10-GbE multi-source agreement) [3], a 10 Gb s\(^{-1}\) DML needs to be cost-effective, operated at a low operating current, and maintain a high single-mode stability at the predetermined wavelength channel [4, 5].

From the viewpoint of stable single-longitudinal mode operation, channel wavelength controllability, and integration compatibility with other functional devices, a \(\lambda/4\)-shifted distributed feedback laser diode (DFB LD) with anti-reflection (AR)-coated facets is an idealized source [4–7]. Such an LD is usually fabricated in two types of waveguides: a ridge waveguide (RWG) and a buried heterostructure (BH). The BH type has many advantages over an RWG, such as a lower power consumption (i.e., lower threshold current and lower thermal resistance) and better output beam quality (i.e., more circular and stable spatial mode). Although a conventional BH type with a current blocking structure consisting of p-/n-/p-InP layers shows an excellent current blocking property (i.e., a low leakage current), it has two critical problems. One is a large optical loss owing to the Zn-diffusion of the p-InP...
layer into both ends of the active region, and the other is a low modulation bandwidth from the large parasitic capacitance of the blocking structure.

To prevent this Zn-diffusion and reduce the parasitic capacitance, it may be effective to use an insulating layer in the current blocking structure. It was previously reported that the parasitic capacitance can be decreased by inserting a thick Fe-doped semi-insulating InP layer (si-InP) (i.e., si-(1 μm thick)/n-InP, si-(1 μm thick)/n-/si-(1.5 μm thick)/n-InP, and p-/n-/si-(1.5 μm thick)/n-InP) [8]. However, the use of an Fe-doped si-InP layer increases the leakage current outside the active region because of the strong inter-diffusion with p-type dopants [9, 10]; moreover, the insertion of an si-InP layer between the n-InP layers requires a change in the reactor during the growth of the current blocking layers, which in turn increases the fabrication complexity and cost.

As a simple alternative technique, the use of a thinner undoped-InP layer (u-InP) between the side walls of the etched active region and the p-InP layer in the current blocking structure (i.e., u-/p-/n-/p-InP layers) can greatly suppress the Zn-diffusion of the p-InP layer because the Zn diffusion length is reduced to less than 0.1 μm in this type of structure [11]; in addition, it prevents a leakage current outside the active region, and the use of a narrow etched mesa (EM) structure can reduce the parasitic capacitance of the blocking structure according to the parallel plate model. These techniques are attractive from the viewpoint of fabrication simplicity and cost effectiveness. In this paper, we describe the fabrication of 1.5 μm etched-mesa buried heterostructure (EMBH) λ/4-shifted DFB-LDs with a narrow-type EMBH, where the current blocking structure consists of u-/p-/n-/p-InP layers. In addition, we tested their static and dynamic properties using various mesa widths. Finally, for this optimized structure, a 2 km transmission test was conducted.

2. Device structure

Figure 1 shows a schematic cross-sectional view of an EMBH DFB-LD with a u-/p-/n-/p-InP current blocking structure. The epitaxial layers were grown using a lateral-flow-type metal-organic chemical vapor deposition. The layer stacks were nearly the same as in our previous RWG DFB-LDs [4] with the exception of the current blocking structure, the thicknesses and doping concentrations of which are 0.1, 0.9, 0.6, and 0.3 μm, and 0 (unintentionally doped), $5 \times 10^{17}$, $1 \times 10^{18}$, and $5 \times 10^{17}$ cm$^{-3}$, respectively. The grating was designed to have a pitch of 236 nm and its phase shift was located at the center of laser cavity. Nearly rectangular-shaped 50% duty gratings were formed through E-beam writing and dry-etching. On the other hand, to confirm the effect of a 0.1 μm thick u-InP on the L–I characteristics, a p-/n-/p-InP current blocking structure was also grown. The mesa width W contains the active region and current blocking structures and it was made by using dry and wet etchings on the SiN$_x$-patterned wafer.

To examine the effect of the mesa width on the static and dynamic properties, its widths were fabricated as 8 to 40 μm in a chip-bar. After the typical LD fabrication processes were applied, both facets of the 300 μm long DFB-LD chip-bar with various mesa widths were AR-coated using an ion beam deposition of TiO$_2$ and SiO$_2$. In this structure, the normalized grating coupling coefficient $kL$ was designed to be 1.8.

3. Experimental results

Figures 2(a) and (b) show typical L–I–V curves of λ/4-shifted EMBH DFB-LDs with the current blocking structures of u-/p-/n-/p-InP and p-/n-/p-InP for various mesa widths, W, respectively. All measurements were performed at a temperature of 25°C. In L–I curves, the threshold currents and slope efficiencies appear to be about 9.5 to 11 mA and 0.165 to 0.195 W A$^{-1}$ for the u-/p-/n-/p-InP and about 13.5 to 15 mA and 0.17 to 0.185 W A$^{-1}$ for the p-/n-/p-InP, respectively. In L–V curves, the threshold voltages of both structures are shown to be about 0.82 to 0.86 V and the series resistances are estimated to be about 7.2 (for W = 40 μm) to 8.4 Ω (8 μm) for the u-/p-/n-/p-InP and about 6.0 (40 μm) to 7.0 Ω (8 μm) for the p-/n-/p-InP. Based on these results, it is confirmed that the threshold current can be reduced by over 25% and the series resistance can be increased by about 20% by using a 0.1 μm thick u-InP in the current blocking structure.

Figures 3(a) and (b) show output spectra of both DFB-LDs with a W of 8 μm at the current of 50 mA. The side mode suppression ratios (SMSRs) appear to be about 50 dB. For the tested DFB-LD chip-bars, the single-mode-yields of SMSR (i.e., SMSR >40 dB) were obtained to be >95% up to the injection current of 200 mA except at both edges (no AR-coated).

To test the dynamic properties of the DFB-LDs with the current blocking structure of u-/p-/n-/p-InP for various mesa widths, the chip bar was mounted on a copper-tungsten metal optical bench (MOB) containing 45 Ω matching resistors and a flexible printed circuit board, similar to that described in [4] and [5]. Figure 4 shows the electro-optic (EO) responses and return losses of the DFB-LD with a mesa width W of 40, 14,
and 8 μm for various bias currents. It is clearly shown that the −3 dB bandwidth increases considerably with the decrease of W while the return loss still remains low level of about −20 dB. For the DFB-LD with a W of 8 μm, the −3 dB modulation bandwidth appears to be >10 GHz at a bias current of 40 mA. On the other hand, it is found that the curve of return loss tends to be lowered with a decrease in W. For this result, we think that the series resistance of DFB-LDs mounted on the MOB can be reduced owing to the sufficient thermal dissipation.

To examine the effect of the mesa width on the dynamic properties and the parasitic response (i.e., RC limit) quantitatively, we extracted the intrinsic responses from the EO responses measured at different bias currents by applying a frequency response subtraction method [12], and then obtained the parasitic component by subtracting the measured data from the intrinsic response under the assumption that the frequency response of a DML is composed of intrinsic and parasitic responses [8].

Figures 5(a) and (b) show the squared resonance frequency $f_r^2$ of the DFB-LD with the output power at both facets P and the damping rate $\gamma$ with the $f_r^2$ for a mesa width W of 40, 14, and 8 μm, respectively. It appears that the $f_r^2$-P curve is lowered and the $\gamma$-$f_r^2$ curve is raised with a decrease in W. According to the relation between $f_r^2$ and P (i.e., $f_r^2 = AP/(1 + P/P_{sat}$, where A and $P_{sat}$ are modulation efficiency and saturation power, respectively) [13], A, $P_{sat}$, and maximum resonance frequency $f_{r,max} = -((AP_{sat})^{1/2}$) were obtained to be about 18.4 GHz$^2$ mW$^{-1}$, 13.0 mW, 15.4 GHz for W = 40 μm, about 15.3 GHz$^2$ mW$^{-1}$, 15.5 mW, 15.4 GHz for 14 μm, and about 7.5 GHz$^2$ mW$^{-1}$, 43.6 mW, and 18.1 GHz for 8 μm, respectively. From these data, by using the relation $P = (hc/\lambda)V_g\alpha_m S$ (where $hc/\lambda$ is the energy per photon, V is the cavity volume, $v_g$ is group
Figure 4. EO responses and return losses of the DFB-LD (with the u-/p-/n-/p-InP) with a mesa width of 40 μm for (a) and (b), 14 μm for (c) and (d), and 8 μm for (e) and (f), respectively. The bias currents are 20 to 80 mA.
velocity, $\alpha_m$ is the mirror loss, and $S$ is the photon densities) and $\varepsilon S = P/P_{sat}$ (where $\varepsilon$ is the gain compression coefficient), $\varepsilon$ was extracted to be about $3.7 \times 10^{-17}$ cm$^3$ for $W = 40 \mu$m, $3.1 \times 10^{-17}$ cm$^3$ for $14 \mu$m, $1.1 \times 10^{-17}$ cm$^3$ for $8 \mu$m with the values $\lambda = 1.515 \mu$m, $V = 15.1 \mu$m$^3$, $v_g = 0.81 \times 10^8$ m s$^{-1}$, and $\alpha_m = 30$ cm$^{-1}$. The extracted values are in good agreement with that used for multiple quantum well DFB lasers [7].

On the other hand, according to the relation between $f_r^2$ and $\gamma$ (i.e., $\gamma = K f_r^2 + 1/\tau$, where $K$ and $\tau$ are $K$-factor and carrier life time, respectively), the $K$-factor and carrier life time were extracted within the linear region (i.e., below 120 GHz$^2$) and obtained to be about 0.24 and 0.15 ns for $W = 40 \mu$m, about 0.26 and 0.14 ns for $14 \mu$m, and about 0.28 and 0.12 ns for $8 \mu$m, respectively. From these results, we think that the increased $K$-factor and decreased carrier lifetime (with the decrease of $W$) may be closely related to the reduced differential gain and increased carrier densities.

Figure 6 shows the parasitic response of the DFB LD with a mesa width $W$ of 40, 14, and 8 $\mu$m. As the value of $W$ decreases, the parasitic effect is considerably reduced and a large bandwidth is shown in the frequency response. By applying the functional fittings of these results, RC constants for a $W$ of 40, 14, and 8 $\mu$m were obtained as 68.8, 39.2, and 21.5 $\Omega$ $\mu$F, respectively. Based on the results tested for the $\lambda$/4-shifted EMBH DFB-LDs with various mesa widths, we concluded that the optimized mesa width is 8 $\mu$m.

For the DFB-LD with a $W$ of 8 $\mu$m, we conducted a transmission test. Figure 7 shows the eye patterns at the back-to-back (BtB) and after a 2 km transmission. Owing to the sufficient modulation bandwidth of the fabricated LD, the eye patterns are clearly opened with dynamic extinction ratios of about 5 dB (without a filter in the receiver module) and 4.6 dB (with the filter) for before and after the transmission, respectively. Figure 8 shows the BER link performance through 2 km of single mode fiber with respect to the minimum received power, $P_{MR}$. The minimum received power at a BER of $10^{-10}$ was shown to be near $-18$ dBm at the BtB, and increased with a power penalty of $<1$ dB after the transmission.

4. Summary

We developed 1.5 $\mu$m and 10 Gb s$^{-1}$ EMBH $\lambda$/4-shifted DFB-LDs with a $u$-/p-/n-/p-InP layer blocking structure. To examine the effect of the etched-mesa width on the static and dynamic properties, DFB-LDs with various mesa widths were fabricated in a chip-bar. For a 300 $\mu$m long DFB-LD with a mesa width of 8 $\mu$m, a threshold current of about 10 mA, a SMSR of $>50$ dB, and a 3 dB bandwidth of $>10$ GHz at a
A current of 40 mA were achieved. A transmission test for this LD shows a clear eye-opening with a dynamic extinction ratio of >4.5 dB at 10 Gb s\(^{-1}\), and a power penalty of <1 dB after a 2 km transmission. Based on these results, we concluded that our DFB-LD is capable of operating at a data rate of 10 Gb s\(^{-1}\), and can be used as a low-cost light source for 100 Gb s\(^{-1}\) Ethernet transmitters. Research on a multichannel structure based on selective area growth is currently being conducted.

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Figure 7. Eye patterns (a) at the BtB (without a filter in the receiver module) and (b) after a 2 km transmission (with the filter) for the DFB-LD with \(W = 8 \mu m\). The bias currents were 60 mA.

Figure 8. BER link performances of ten channels at the back-to-back (black) and after a 2 km transmission (red) with respect to the minimum received power, \(P_{MR}\).
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