

# GaInAsP/InP distributed reflector laser with phase-shifted DFB and quantum-wire DBR sections

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**Abstract:** A low-threshold-current distributed reflector laser consisting of phase-shifted distributed feedback (DFB) grating and quantum-wire distributed Bragg reflector (DBR) sections was realized. The device with a DFB length of  $150\ \mu\text{m}$ , a DBR length of  $240\ \mu\text{m}$  and a stripe width of  $1.5\ \mu\text{m}$  achieved a threshold current as low as  $1.2\ \text{mA}$  and a differential quantum efficiency of 13% from the front facet under RT-CW conditions. A good single-mode operation was also realized at a mode determined by the phase-shifted grating.

**Keywords:** distributed feedback laser, distributed Bragg reflector, GaInAsP/InP, quantum wire, EB lithography, integration

**Classification:** Photonics devices, circuits, and systems

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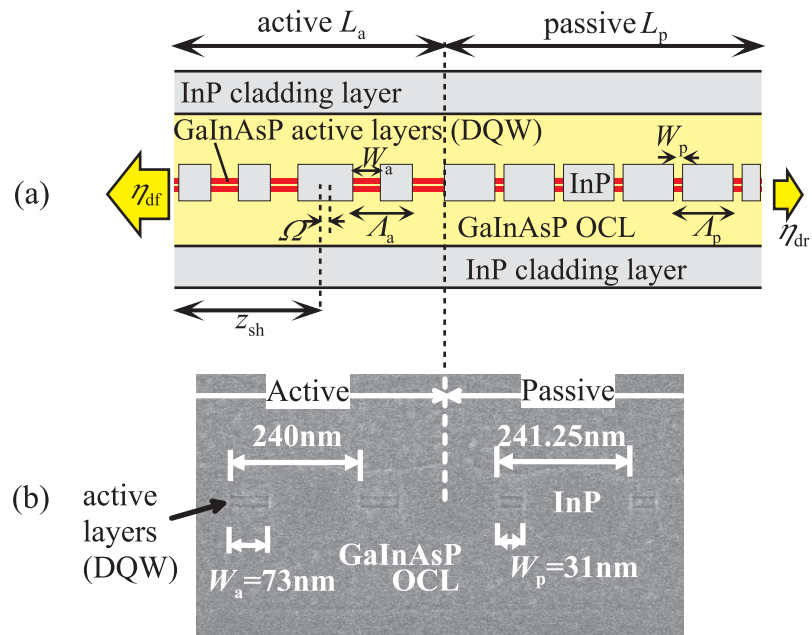
## 1 Introduction

A low-threshold-current operation with a stable single-mode property of a long-wavelength semiconductor laser is very important for a low power consumption and cost-effective components for optical interconnection systems, such as metropolitan area network (MAN) and local area network (LAN) systems. A vertical-cavity surface-emitting laser (VCSEL) has been thus far studied as one of the candidates [1, 2]. In addition, for a high-efficiency operation, a distributed reflector (DR) laser, combining a distributed feedback (DFB) laser and a distributed Bragg reflector (DBR) section, was proposed and its superior static and dynamic characteristics have been investigated [3]. Recently, we have realized a very low threshold current operation of DFB lasers with wirelike active regions because of their strong index coupling and small active medium volume [4], and also demonstrated their reliable operation of more than 8,200 hours under room-temperature continuous-wave (RT-CW) conditions [5]. For further improvement in output efficiency from a single side facet, we proposed a new type of DR laser consisting of DFB and DBR sections with different active wire widths, and realized a high-efficiency operation while maintaining a low threshold current [6, 7].

In this paper, we report a low-threshold-current operation of DR lasers by introducing a  $\lambda/8$ -phase-shift region into the DFB section.

## 2 Device structure and fabrication

The schematic structure and cross-sectional SEM view of the DR grating structure are shown in Figs. 1 (a) and (b), respectively. The DR laser consists of an active DFB section ( $L_a$ ) with wirelike active regions ( $W_a$ ) and a passive DBR section ( $L_p$ ) with narrow active regions ( $W_p$ ), which is a quantum-wire structure. Both sections can be integrated by utilizing the energy blue shift due to the lateral quantum confinement effect [8], *i.e.*, by modulating active region widths. To realize an efficient reflection of the lasing wavelength



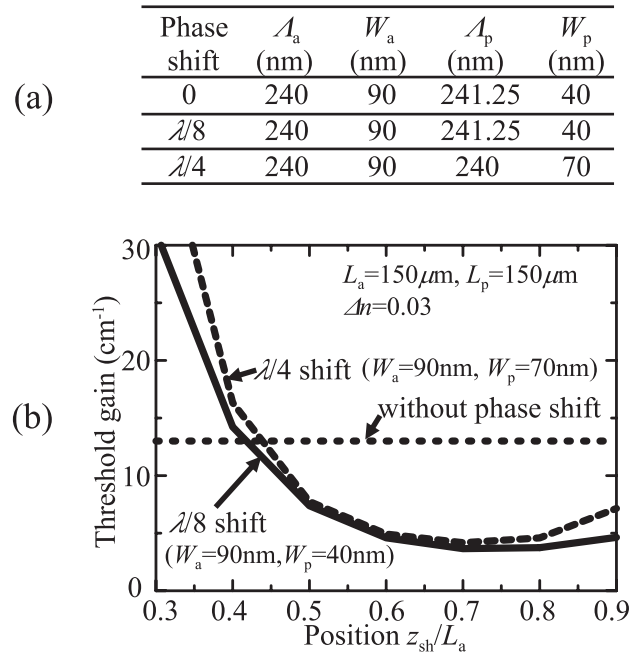
**Fig. 1.** (a) Schematic structure and (b) cross-sectional SEM view of DR grating structure.

towards the front facet, we designed the DBR reflection peak wavelength to match the lasing wavelength (longer-wavelength side of the stopband of the DFB section) by changing the grating periods of the active ( $\Lambda_a$ ) and passive ( $\Lambda_p$ ) sections. The phase-shift ( $\Omega$ ) position from the front facet is indicated by  $z_{sh}$ . The introduction of a phase-shift region at an appropriate position in the active DFB section would lead to a low-threshold-current operation at a phase-shift mode due to its strong longitudinal mode confinement.

Figure 1 (b) shows a cross-sectional SEM view of the grating at the junction of the active and passive sections. The wire widths of the active and passive sections were measured to be 73 nm and 31 nm with the periods of 240 nm and 241.25 nm, respectively. A DBR section with a high reflectivity is essential for realizing a low-threshold and high-efficiency operation. Thus, we investigated the reflectivity of the DBR section theoretically and experimentally, and it was found that a reflectivity of more than 95% can be achieved using the active region width  $W_p = 40 \sim 80\text{ nm}$ . Details are shown in a previously reported paper [5].

Figure 2 (b) shows the threshold gain for the DR laser with the phase-shifted DFB section as a function of phase-shift position ( $z_{sh}/L_a$ ) for three phase-shift amounts (0,  $\lambda/8$ , and  $\lambda/4$ ) listed in Fig. 2 (a). The active and passive section lengths were assumed to be  $150\text{ }\mu\text{m}$ . The refractive-index difference ( $\Delta n$ ) between a gain and a nongain region is 0.03, which is typical for a grating structure with periodically etched active regions. Grating structures for all devices were designed so as to match the DBR reflection peak to the lasing wavelength using the parameters shown in Fig. 2 (b).

The threshold gain of the  $\lambda/8$ -phase-shifted DR laser is smaller than that of the  $\lambda/4$ -phase-shifted DR laser in the entire phase-shift position range.



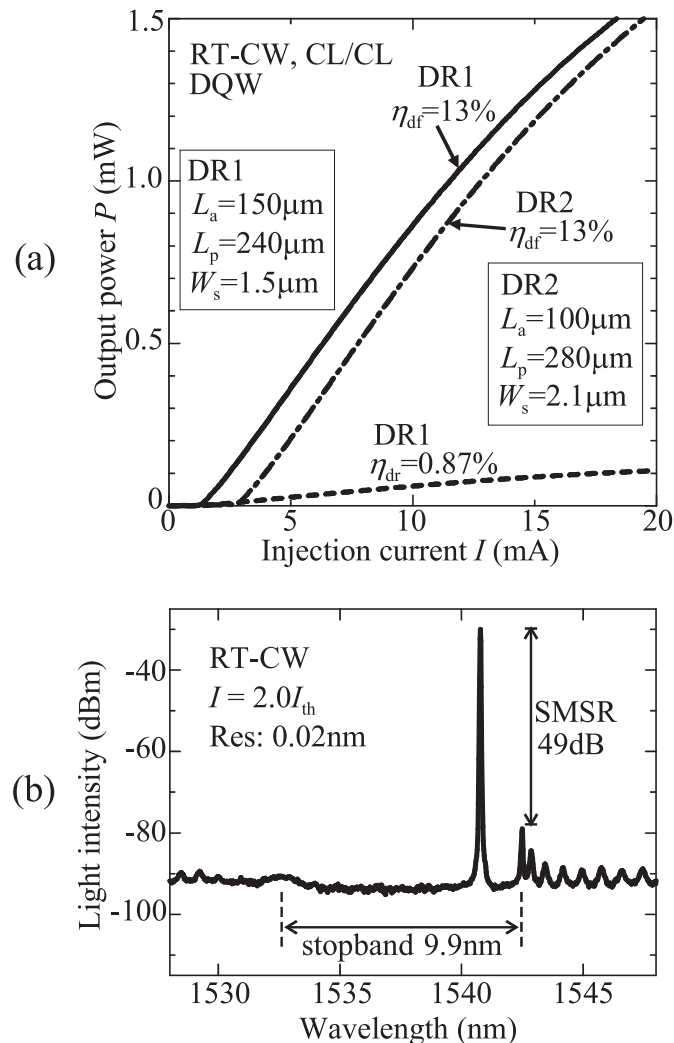
**Fig. 2.** (a) Grating designs of DR lasers and (b) threshold gain dependence on phase-shift position.

This result is attributed to the trade-off between the mirror loss ( $\alpha_m$ ) for the lasing wavelength and the gain-matching effect [9]. The mirror loss  $\alpha_m$  is smaller in the case of  $\Omega = \lambda/4$  than in the case of  $\Omega = \lambda/8$ . However, the gain-matching effect, which means a longitudinal optical confinement factor, is larger for the  $\lambda/8$ -shifted DR laser than for the  $\lambda/4$ -shifted laser because of the difference in the standing-wave profile in the cavity. In addition, the appropriate position of the  $\lambda/8$ -phase-shift region for obtaining the lowest threshold gain is  $z_{sh}/L_a = 0.7 \sim 0.8$ . In the case that the phase shift is almost near the front facet, that is, a small  $z_{sh}/L_a$ , the oscillation will occur at the mode on the long wavelength edge of the stopband, as in the case of the grating without a phase shift.

DR lasers with a phase-shifted grating were fabricated by electron-beam (EB) lithography,  $\text{CH}_4/\text{H}_2$  reactive ion etching (RIE) and organometallic vapor phase epitaxy (OMVPE) [4]. A strain-compensated (SC) double-quantum-well (DQW) structure was prepared on a  $\text{p}^+$ -InP substrate as an initial wafer, which consists of two 7-nm-thick  $\text{Ga}_{0.22}\text{In}_{0.78}\text{As}_{0.81}\text{P}_{0.19}$  1% compressively strained (CS)-QW layers and three 10-nm-thick  $\text{Ga}_{0.25}\text{In}_{0.75}\text{As}_{0.50}\text{P}_{0.50}$  0.15% tensile-strained (TS) barrier layers. The phase-shifted grating structure was fabricated by only changing the EB lithography patterns. The index-coupling coefficients of the two sections were estimated from the cross-sectional structures to be  $340 \text{ cm}^{-1}$  and  $160 \text{ cm}^{-1}$ , respectively. A very small transition region ( $< 250 \text{ nm}$ ) was successfully fabricated. Therefore, this integration method can be applied to a high-density integration of photonic devices.

### 3 Lasing characteristics

Figure 3 (a) shows the light-output characteristics of the fabricated DR lasers with the  $\lambda/8$ -phase-shifted DFB section under RT-CW conditions. A low threshold current of 1.2 mA was obtained for the active section length ( $L_a$ ) of 150  $\mu\text{m}$  and the passive section length ( $L_p$ ) of 240  $\mu\text{m}$  (DR1). The stripe width ( $W_s$ ) was 1.5  $\mu\text{m}$  and the phase shift position ( $z_{\text{sh}}/L_a$ ) was 0.5. The external differential quantum efficiencies from the front ( $\eta_{\text{df}}$ ) and rear ( $\eta_{\text{dr}}$ ) facets were measured to be 13% and 0.87%. For another device (DR2), a threshold current of 2.8 mA and an  $\eta_{\text{df}}$  of 13% were obtained for  $L_a = 100 \mu\text{m}$ ,  $L_p = 280 \mu\text{m}$ ,  $W_s = 2.1 \mu\text{m}$  and  $z_{\text{sh}}/L_a = 0.25$ . The relatively low output efficiency might be caused by the strong optical field confinement into the cavity due to the phase-shifted grating and the facet phase of the grating. In addition, the DBR reflection peak might differ from the lasing wavelength because the active region widths of the DFB and DBR sections were slightly different from those we designed. Both the DR1 and DR2 devices also showed



**Fig. 3.** (a) I-L characteristics of DR lasers from front and rear facets and (b) lasing spectrum of DR laser (DR2) at  $I = 2I_{\text{th}}$  under RT-CW conditions.

good single-mode properties. Figure 3 (b) shows the lasing spectrum of DR2 under RT-CW conditions, which was measured with a resolution of 0.02 nm. The lasing wavelength was observed inside the stopband due to the effect of the  $\lambda/8$ -phase-shifted grating. A stable single-mode operation was achieved with a submode suppression ratio (SMSR) of 49 dB at a bias current of twice the threshold current. The index-coupling coefficient of the active section was estimated to be  $340 \text{ cm}^{-1}$  from the stopband width of 9.9 nm; this value was almost the same as that calculated from the cross-sectional structures shown in Fig. 1 (b).

#### 4 Conclusion

We achieved a low-threshold-current and stable single-mode operation of a DR laser with phase-shifted DFB and high-reflection DBR sections. From the theoretical analysis of the phase shift, it was found that the introduction of a  $\lambda/8$ -phase-shift region into the DFB section is appropriate for a low-threshold-current operation. A low threshold current of 1.2 mA and a differential quantum efficiency of 13% from the front facet were obtained for the active DFB section length of  $150 \mu\text{m}$ , the passive DBR section length of  $240 \mu\text{m}$  and the stripe width of  $1.5 \mu\text{m}$ . A stable single-mode operation due to the phase-shifted grating was clearly observed.

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