Membrane Distributed-reflector Lasers

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Abstract: *1.55 μm wavelength GaInAsP/InP membrane distributed-reflector lasers for on-chip optical interconnects will be presented. Fairly low threshold current (250 μA) and asymmetric output characteristic were obtained with the DFB section length of 30 μm.*
Keywords: *Semiconductor laser; Distributed Bragg reflector; Distributed feedback; Membrane laser; GaInAsP/InP; Optical interconnect*

I. Introduction

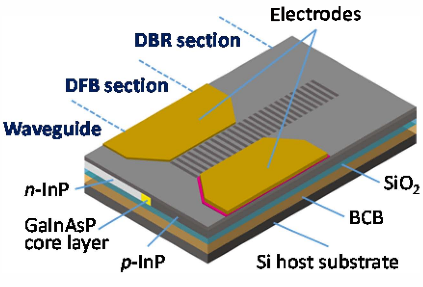
We have proposed a distributed-reflector laser, DR laser for short, which consists of an active distributed-feedback (DFB) and a passive distributed-Bragg-reflector (DBR) sections so as to increase the output from one side of the cavity without interrupting superior single-mode characteristics [1]. Fundamental operation properties such as sub-mode suppression ratio (SMSR), an asymmetric output, and a narrow linewidth, have been reported for DR lasers with multiple-quantum-well (MQW) active region [2]-[4]. After demonstrating low threshold current density and low threshold current operations of DFB lasers by adopting wirelike active regions [5],[6], we have introduced the wirelike active regions into DR lasers [7] and achieved fairly low threshold current (0.9 mA) as well as relatively high external differential quantum efficiency (48%) from one side of the cavity [8]. A modulation current efficiency (MCEF) under a high-speed direct modulation, i.e. the slope of the resonance-like frequency f_r as a function of the square root of the bias current above the threshold $(I_b-I_{th})^{1/2}$, of this type of DR laser was reported to be 3.0 GHz/mA$^{1/2}$ [9]. Since DR lasers don't need high reflective facets for high efficiency operation, they are suitable for monolithic integration with other elements and the developments for high-speed optical fiber communications are undergoing [10],[11].

Even though DFB and DR lasers consisting of wirelike active regions showed low threshold current (< 1 mA) and moderately high differential quantum efficiency (~ 50% from one side of the cavity), they are suitable for low power-consumption operation at an output power of a few mW range. Then we proposed a new class of semiconductor lasers by utilizing a thin semiconductor membrane structure sandwiched by low refractive-index claddings so as to enhance an optical confinement into the active region and demonstrated low threshold membrane DFB laser [12]-[14].

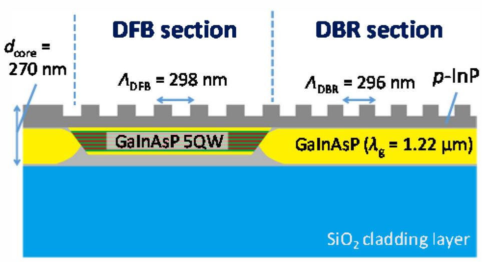
On the other hand, ultra-low power consumption and high-speed operation of semiconductor lasers has been required for on-chip optical interconnects for next generation LSIs, however required pulse energy for the optical link was predicted to be 100 fJ/bit or the less [15] which corresponds to the power consumption of only 1 mW for the transmission speed [1]of 10 Gbit/s, and would be much lower in future [16]. For this purpose, high-speed (> 10 Gbit/s) optical modulators or current injection type lasers capable of ultra-low power consumption operation are indispensable. To meet such a requirement, we have been investigating injection-type membrane DFB and DR lasers bonded on another host InP or Si substrate. Here recent results obtained for these membrane lasers are reviewed.

II. Static Operation Characteristics of Membrane DR Laser

Since the minimum receivable power of a typical PIN-photodiode (PD) used for long wavelength optical fiber communications is -13 dBm (approximately 50 μW) for 10 Gbit/s signals with a bit-error-rate (BER) of 10^{-9}, the required output power of the light source will be of the order of hundreds of μW, the optical pulse energy is in the order of tens of fJ/bit. When we consider the possibility of directly modulated semiconductor lasers for on-chip optical interconnects, a threshold current of much lower than 1 mA and the direct modulation speed higher than 10 GHz at a



(a)



(b)

Fig. 1. (a) Schematic structure of a LCI-membrane-DR laser and (b) its cross-sectional structure [20].

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bias current of 1 mA will be required, and the DFB laser with wirelike active regions can't meet this requirement. Therefore we need to reduce the operation current of semiconductor lasers such as an enhancement of the optical gain of the active region by well size-controlled low-dimensional quantum structures, or by a strong optical confinement into an extremely small laser cavity by photonic-crystal structures. We proposed to enhance it by using a thin semiconductor layer (membrane) sandwiched by low refractive-index materials such as BCB or SiO_2 so as to strongly confine the optical field into the active region of the semiconductor membrane structure [12]. The optical confinement factor of multiple-quantum-well structures is enhanced by reducing the core thickness d_{core} and it is approximately 3%/quantum-well which is around 3 times higher than that in conventional QW lasers [17]. This enhancement also increases an index-coupling coefficient κ_i of DFB and DBR structures, hence the threshold current of membrane DFB and DR lasers can be reduced to one order of magnitude lower than that of conventional ones.

Figure 1(a) shows a schematic of a lateral-current-injection (LCI)-membrane DR laser. It consists of an active DFB section and a passive DBR section. The passive waveguide was formed by the BJB regrowth process and the DFB and DBR structures were realized by a surface grating structure [18]. The DBR at one side of the DFB structure facilitates concentration of the light output at the opposite side of the DFB structure. Figure 1(b) shows the cross section along the cavity direction of the LCI-membrane DR laser. We adopted a period at the DFB section, ΛDFB, of 298 nm and that at the DBR section, ΛDBR, of 296 nm in order to match the lasing wavelength to the Bragg wavelength of the DBR section. A small reduction in the period at the DBR section of the membrane laser is needed because the membrane DFB laser with surface grating typically operates at the shorter wavelength side of the stop band because of its strong optical confinement to the low index region of the grating [19].

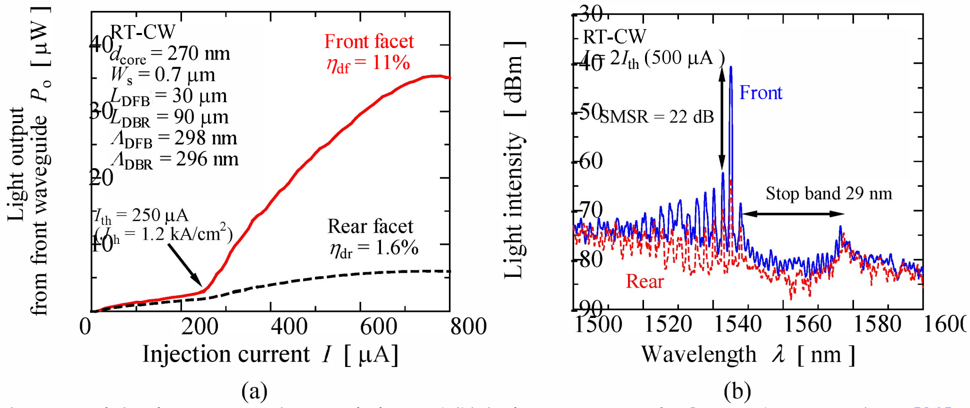

Fig. 2. (a) Light output-injection current characteristics and (b) lasing spectrum of LCI-membrane DR laser [20].

Figure 2(a) shows the light output characteristics of the LCI-membrane DR laser with d_{core}=270 nm, stripe width, W_s=0.7 µm, DFB section length, L_{DFB}=30 µm, and DBR section length, L_{DBR}=90 µm. The device was formed by cleavage and had an approximately 200 µm-long waveguide at the front side and a 100 µm-long waveguide at the rear side. A threshold current of I_{th}=250 µA, an external differential quantum efficiency at the front side of η_{df}=11% (indicated by the solid line) and that at the rear side of η_{dr}=1.6% (indicated by the dashed line) were obtained. An asymmetric output ratio of 6.7 can be attributed to high reflectivity DBR. The lasing spectrum of the device at a bias current of 2I_{th} is shown in Fig. 2(b), where a single mode operation at 1545 nm with a side-mode suppression-ratio (SMSR) of 22 dB, and a stopband width of 29 nm (κ_i was estimated to be 1300 cm^{-1}) were observed.

III. HIGH-SPEED DIRECT MODULATION CHARACTERISTICS OF DFB LASER

Since the enhancement of the optical confinement factor in the membrane structure is effective not only for a reduction of the threshold current but also for an increase of a modulation efficiency (slope of the 3dB bandwidth

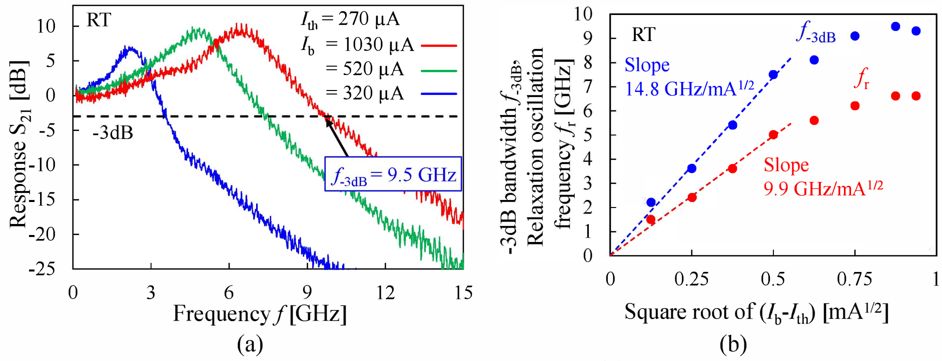

Fig. 3. (a) Small-signal frequency response of membrane DFB laser and its (b) relaxation oscillation frequency and -3 dB bandwidth frequency as a function of square root of the bias current obtained from small signal frequency response [21].

normalized by a square root of a bias current above the threshold), we measured direct modulation characteristics of a membrane DFB laser. The device consisting of d_{core}=270 nm, W_s=0.7 μm, L_{DFB}=80 μm, and 600 μm-long passive waveguide section showed I_{th}=270 μA and η_{df}=12%. As can be seen in Fi. 3(a), the maximum -3 dB bandwidth of 9.5 GHz was obtained at a bias current of 1.03 mA (3.8I_{th}). Figure 3(b) shows the relaxation oscillation frequency f_r and -3 dB bandwidth f_{-3dB} as a function of the square root of the bias current. The slope of relaxation oscillation frequency and -3 dB bandwidth are 9.9 GHz/mA$^{1/2}$ and 14.8 GHz/mA$^{1/2}$, respectively, which are approximately more than 2 times higher than those reported for conventional DFB lasers [21]. Much higher modulation efficiency was reported for a lambda-scale embedded active region photonic-crystal (LEAP) laser [22], which utilizes the membrane structure with 2D photonic-crystal structure.

IV. CONCLUSIONS

The present status of membrane-based DFB and DR lasers is reviewed. Even though there still remains problems to be solved for on-chip optical interconnects, the idea of strong optical confinement into a thin semiconductor membrane structure will lead to miniature photonic devices with ultra-low power-consumption operation in future.

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