High Modulation Efficiency of Sub-milliampere Threshold GaInAsP/InP Membrane DFB Laser

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Abstract- Direct modulation of membrane DFB laser was carried out. Small signal response showed -3dB bandwidth of 9.5 GHz at a bias current of 1 mA. This corresponds to modulation current efficiency factor of 9.8 GHz/mA$^{1/2}$.

I. INTRODUCTION

Electrical interconnection has bottlenecks such as RC delay and joule heating. Recently, the optical interconnection technology is used in board-to-board and chip-to-chip interconnection instead of the electrical one because optical interconnection can overcome aforementioned problems. Furthermore, on-chip optical interconnection is one of attractive applications of extremely low power consumption photonic devices and circuits [1]. We proposed and demonstrated membrane DFB lasers for this purpose since they are suitable for high-speed direct modulation under very low operating current [2]. In the semiconductor membrane structure, which consists of a thin semiconductor core layer sandwiched by low refractive-index dielectric cladding layers, the optical confinement factor of the active layer and the index-coupling coefficient of the grating can be enhanced by a factor of around 3. Therefore, not only an ultra-low threshold operation but also a high-speed direct modulation under very low bias current can be expected with short cavity DFB structure.

We demonstrated sub-mA threshold operation of lateral-current-injection (LCI) membrane DFB laser prepared on a Si substrate by using benzocyclobutene (BCB) adhesive bonding [3], and its integration with a p-i-n-photodiode (PIN-PD) by butt-jointed built-in (BJB) structure [4]. However, dynamic characteristics of LCI membrane DFB laser under a high-speed direct modulation were not reported.

In this work, we report the dynamic properties of LCI membrane DFB laser on Si substrate. The device exhibited the -3dB bandwidth of 9.5 GHz at a bias current of 1.04 mA (3.85 I_{th}) which corresponds to modulation-current-efficiency-factor (MCEF) of 9.8 GHz/mA$^{1/2}$.

II. DEVICE STRUCTURE

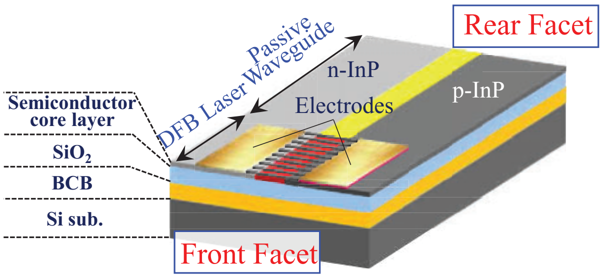

Fig. 1 Device structure.

Figure 1 shows a schematic diagram of the LCI membrane DFB laser on a Si substrate. The detail fabrication procedure was described in ref. [3]. A 270-nm-thick semiconductor layer was bonded on a p-Si substrate by using 2-μm-thick BCB adhesive layer and 1-μm-thick SiO$_2$ cladding layer. The active layer consists of five 1% compressively strained $Ga_{0.22}In_{0.78}As_{0.81}P_{0.19}$ quantum-wells (6 nm each) with 0.15% tensile strained $Ga_{0.26}In_{0.74}As_{0.49}P_{0.51}$ barriers (10 nm each) sandwiched by $Ga_{0.21}In_{0.79}As_{0.49}P_{0.51}$ optical confinement layers (15 nm each), and InP cap layers (50 nm and 100 nm). The lateral junction pin diode structure was fabricated by two-step regrowth of organometallic vapor phase epitaxy. A 50-nm deep grating with the period of 298 nm was formed on the surface of a p-InP cap layer by an electron beam lithography. The device had BJB waveguide so as to integrate with other components. To measure the light output of the laser, one side facet was formed within the active region and the other facet was formed within the passive waveguide region because the DFB cavity length was very short for handling. The stripe width of the active region was 0.7 μm, and lengths of the DFB laser cavity and the passive waveguide were 80 μm and 600 μm, respectively.

III. DEVICE CHARACTERISTICS

Figure 2 shows light output versus current (L-I) characteristic measured from the front facet under room-temperature continuous-wave condition. A threshold current I_{th} of 0.27 mA (threshold current density J_{th} = 480 A/cm^2) and an external differential quantum efficiency of 12% (front facet) were obtained. Lasing spectrum was measured with different bias currents as shown in Fig. 3. At a bias current of 0.41 mA, a lasing wavelength was 1533 nm. The stopband width was 32 nm which corresponds to an index-coupling coefficient κ_i of 1500 cm^{-1}. When the bias current was increased to 0.66 mA, longitudinal multimode operation was observed.

Figure 4 shows the small signal modulation response (S_{21}) measured by a vector network analyzer. The electrical signal was injected through a 20G high speed probe directly to the

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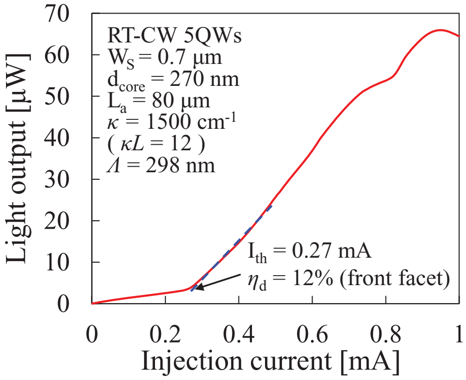

Fig. 2 Light output versus current characteristics

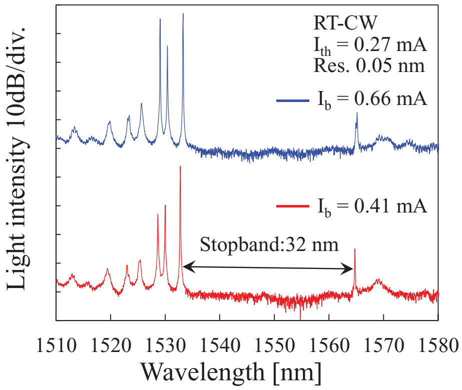

Fig. 3 Lasing spectrum with two bias current conditions.

chip without impedance matching and the optical signal was received by a 20G photoreceiver. The -3dB small signal modulation bandwidth of approximately 9.5 GHz was obtained at a bias current (I_b) of 1.04 mA.

The square root of (I_b-I_{th}) dependence of relaxation frequency obtained from small signal response is plotted in Fig. 5. The linear interpolation shows the MCEF of 9.8 GHz/mA$^{1/2}$, which is, to our knowledge, the highest value among previously reported DFB lasers [5]. The kink at square root of (I_b-I_{th}) = 0.5 mA$^{1/2}$ can be attributed to longitudinal multimode operation, caused from the mismatch between the gain peak wavelength and the Bragg wavelength, as shown in Fig. 3 . If stable single-mode operation is obtained, the relaxation frequency f_r of 8.6 GHz, which corresponds to the -3dB bandwidth of approximately 13 GHz, is expected at a bias current of 1 mA.

IV. CONCLUSION

In conclusion, small signal modulation response of LCI membrane DFB laser bonded on a Si substrate was measured. A low threshold current I_{th} of 0.27 mA and a differential quantum efficiency η_d from the front facet of 12% were obtained for the device with stripe width of 0.7 µm and the cavity length of 80 µm. The stopband width was measured to be 32 nm (κ_i = 1500 cm^{-1}). From small signal modulation, -3dB bandwidth of 9.5 GHz at a bias current of 1.04 mA and the MCEF of 9.8 GHz/mA$^{1/2}$, which is the highest value ever reported for DFB lasers, were obtained. This work shows that direct modulation ability with low threshold current of membrane DFB laser for on-chip interconnection.

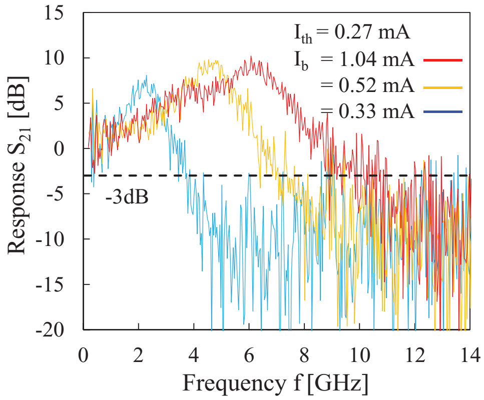

Fig. 4 Small signal modulation response.

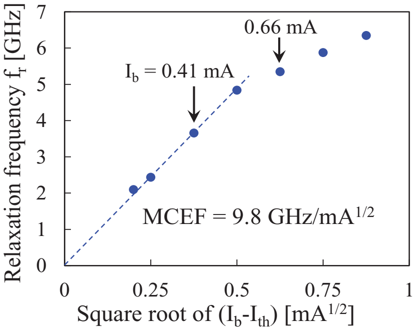

Fig. 5 Relaxation frequancy obtained from small signal modulation response.

ACKNOWLEDGMENT

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