Process-tolerant III-V/Si Membrane Distributed Reflector Lasers and 50-Gb/s Direct Modulation at 80°C

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Abstract: We demonstrate distributed reflector lasers based on a III-V/Si membrane platform that includes quantum well intermixed distributed Bragg reflectors offering tolerance to fabrication errors. The laser was used to transmit 50-Gb/s PAM4 signals at 80°C. © 2024 The Author(s)

1. Background

In Si photonics, most optical modulators (Mach-Zehnder or ring-based) modulate their refractive index through the carrier plasma effect. Such modulators can be operated over a wide temperature range, as well as operate uncooled, although doing so might require the bias point of the modulators to be controlled [1]. There are a few reports that have reported integrated light sources on chip [2], and most of the others used temperature-controlled off-chip lasers [3]. We believe the energy consumption of photonics chips could be further reduced if there were uncooled directly modulated lasers (DMLs) with short cavity ~100 μm on Si photonic chips.

We have developed InP-based lasers on Si substrate. Thin InP-based membranes (typical thicknesses of 230 – 340 nm) were formed on Si waveguides or thermally oxidized Si substrates, and narrow multiple quantum well (MQW) active regions were embedded in the membrane. The very high optical confinement to the MQW and relatively high coupling coefficients of gratings enabled multiple channel DMLs for space division multiplexing [4] or wavelength division multiplexing [5] to be fabricated. However, high-temperature operation has been an issue because of the small active size. To overcome this, a distributed reflector (DR) laser consisting of distributed feedback (DFB) and distributed Bragg reflector (DBR) sections is a potential solution because the DBR section helps maintain the Q-factor for short-cavity lasers. However, the phase and Bragg wavelength mismatch between the DFB and DBR sections is a serious problem in terms of process tolerance because we have used different waveguide structures for the two sections.

In this paper, we describe our new membrane laser cavity consisting of DR lasers with quantum well intermixed (QWI) DBRs. We could easily attain a perfect refractive index matching between the DFB sections and DBR sections without any special process treatment. Furthermore, we could reduce the threshold current and modulate the laser with a 50-Gb/s PAM4 signal at 80°C.

2. Device Structure and Fabrication

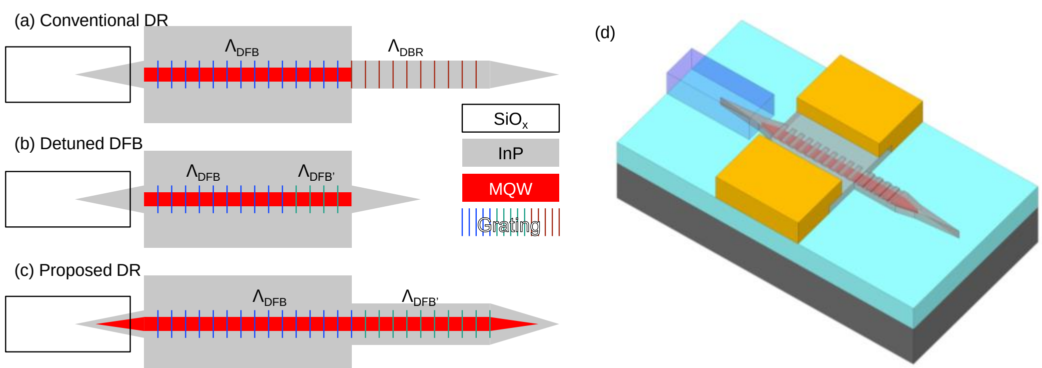

Fig. 1. Top-view schematic structure of (a) conventional DR, (b) detuned DFB, (c) proposed DR, and (d) bird's eye schematic diagram of proposed DR lasers.

Figure 1 shows schematic diagrams of III-V membrane lasers. Figure 1(a) illustrates the previous developed DR laser which consists of a DFB section with a uniform grating and a DBR section where the Bragg wavelength is shifted to obtain single mode lasing [5]. It is difficult to obtain perfect wavelength matching between DFB and

DBR sections, because the mode fields and effective indices of the waveguides are different (the DBR section consists of a InP channel waveguide). To obtain fine enough wavelength alignment, it is required to keep the III-V thickness tolerance within 3 nm, which is not easy to do after the regrowth process. Furthermore, the phase mismatch is induced between these sections because the position of the active region edge is difficult to control accurately.

Figure 1(b) shows the cavity of detuned DFB lasers. The cavity consists of a single gain region, but the Bragg wavelength of the rear section (typical lengths were 10 – 20 μm) is shifted by approximately half of the stopband width, so that the rear section acts as a DBR mirror. The effective indices between the front DFB and rear feedback region are automatically aligned because they have the same structure. This is suitable for a higher yield and lasing wavelength control, and we have reported multiple types of lasers [5-6]. However, the current injected into the rear feedback region did not effectively contribute to lasing, so the threshold current and operating energy tended to be a bit high.

To solve the remaining problems, we devised a new DR laser. Schematic diagrams of it are shown in Fig. 1(c) (plan view) and Fig. 1(d) (bird's eye view). The DBR section employs buried heterostructure (BH) gain media that is same as the DFB section, but we used a quantum well intermixing technique in order to use the BH as a passive waveguide. The effective indices between the DFB and DBR sections are well aligned because their material and structures are the same (the MQWs are intermixed, though). Also, 100% of the DFB section contributes to lasing, so we expect that the proposed structure will have more effective lasing.

Device fabrication was similar to what we have reported elsewhere [5]. First, we grew InGaAlAs 6-QW gain layers sandwiched by InP and an InGaAs etch-stop layer on 2-inch InP substrates. The InP epitaxial wafers were bonded on thermally oxidized Si wafers by oxygen plasma assisted hydrophilic bonding. InP wafers were mechanically lapped and wet-etched; then, the InGaAlAs-based MQW gain membrane was formed on the Si wafers. After the bonding process, MQWs were partially etched and regrown by using u-InP to form BHs. We used Si-ion implantation and Zn thermal diffusion to form lateral p-i-n junctions. During the Si implantation step, we also implanted DBR sections to intermix the MQWs. The thin InP surface layer was patterned and etched to form surface gratings. InP waveguides were formed by dry-etching, followed by metallization of III-V. Finally, spot-size converters based on SiO_x dielectric waveguides were formed on the devices.

3. Experimental Results

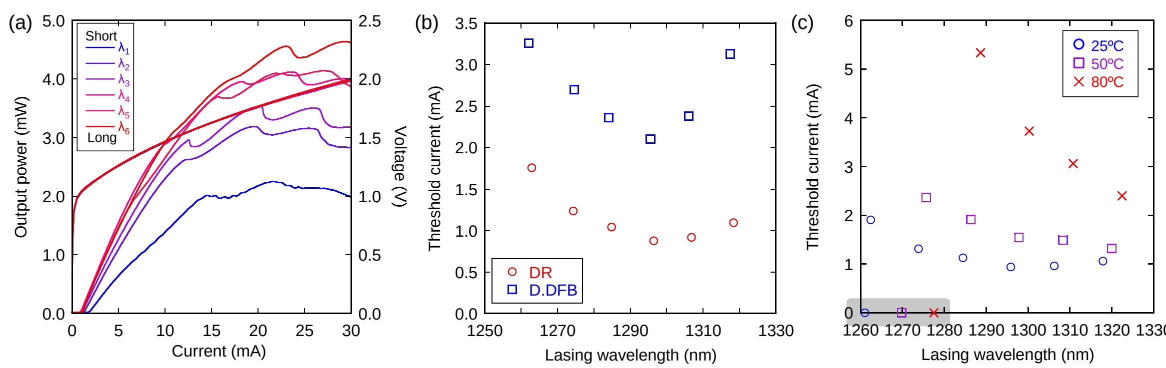

Fig. 2. (a) Output power versus injected current of six of the proposed DR lasers with various lasing wavelengths. (b) Threshold current versus lasing wavelength of proposed DR lasers and conventional detuned DFB lasers fabricated on the same wafer. (c) Threshold current versus lasing wavelength of proposed DR lasers with a stage temperature ranging from 25 to 80°C. Plots in the gray hatched region are the PL peak wavelengths at each temperature.

The fabricated wafers were blade diced into bars and chucked on a temperature-controlled stage. First, we measured the output power while scanning the injected current by using a free-space optical power meter. The output power and the applied voltage versus injected current (L-I-V characteristics) are shown in Fig. 2(a). The results are for six LDs with different lasing wavelengths. The LD with the shortest wavelength (blue plot) had the highest threshold current, and the threshold current could be decreased by increasing the lasing wavelength (purple – red plots). Next, we attached a high-NA fiber to the samples and measured the lasing wavelengths. Figure 2(b) shows the threshold currents of the new DR lasers (red circle plots) and conventional detuned DFB lasers (blue square plots) fabricated on the same wafer at 25°C. With the new structure, we could decrease the threshold current to about half that of the conventional ones, and the minimum threshold current was 0.88 mA at a lasing wavelength of 1296.4 nm. After that, we increased the stage temperature to 50 or 80°C and measured the threshold currents of the six lasers (Fig. 2(c)). We also measured the photoluminescence (PL) spectrum at each temperature; the peak wavelengths are included in the gray hatched region in Fig. 2(c). At 25°C, optimum detuning between the PL peak wavelength and the lasing wavelength having minimum threshold current was approximately 35 nm. However, none of the lasers in this experiment reached the minimum threshold current at 80°C. The laser with the longest lasing wavelength (1322.5 nm, detuned from the PL peak wavelength by approximately 45 nm) had a minimum threshold current of 2.4 mA.

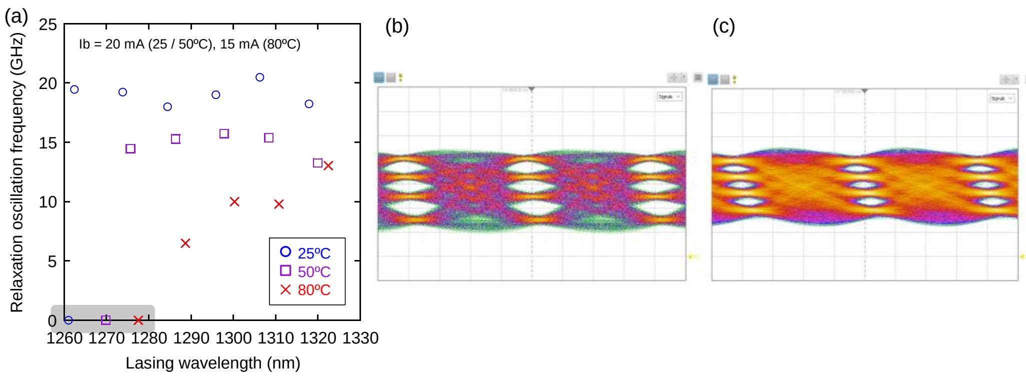

Fig. 3. (a) Relaxation oscillation frequency of DR lasers with stage temperature ranging from 25 to 80°C. PAM4 eye diagram of DR laser at (b) 25°C and (c) 80°C with a bias current of 15 mA.

After that, we measured the relative intensity noise spectra of the lasers while varying stage temperature from 25 to 80°C and extracted the relaxation oscillation frequencies (f_r). The results are plotted in Fig. 3(a) as a function of lasing wavelength. f_r ranged from 18 to 21 GHz at 25°C and a bias current of 20 mA. The maximum f_r was 13 GHz at 80°C and a bias current of 15 mA. It is expected that f_r could be improved a bit by making the lasing wavelength longer. Finally, we directly modulated the laser with the longest wavelength at a bit rate of 50 Gb/s (25 GBaud PAM4) by using a pulse pattern generator. The current source was supplied via a bias tee, and output light from the laser was monitored by a sampling oscilloscope with a 5-tap TDECQ equalizer. Figures 3(b) and 3(c) show eye diagrams at 25 and 80°C with a bias current of 15 mA. At 25°C, the laser had enough bandwidth and we obtained an outer extinction ratio and outer OMA of 4.4 dB and 1.09 mW, respectively. At 80°C, both output power and bandwidth decreased, and the outer extinction ratio and the outer OMA were 3.3 dB and 0.29 mW, respectively.

4. Conclusions

We fabricated and experimentally evaluated our new distributed reflector lasers that use quantum well intermixed distributed Bragg reflectors. The threshold current was reduced to approximately half that of the conventional detuned DFB lasers, and the DR lasers could be directly modulated with a bit rate of 50 Gb/s (PAM4 signal) at a maximum temperature of 80°C. Unfortunately, the fabricated lasers could not reach the minimum threshold current and maximum f_r at 80°C, but we expect a further improvement can be had by using an appropriate lasing wavelength.

5. References

[1] K. Goi et al., "Low-Voltage Silicon Mach-Zehnder Modulator Operating at High Temperatures without Thermo-Electric Cooling," in Proc. OFC 2016, paper W2A.23.
[2] R. Kumar et al., "Demonstration of a hybrid III-V/Si multi-wavelength DFB laser for high-bandwidth density I/O applications," in Proc. OFC 2022, paper Tu2E.5.
[3] C. Sun et al., "TeraPHY: An O-band WDM Electro-optic Platform for Low Power, Terabit/s Optical I/O," in Proc. VLSI Symposium 2020, paper JFS1.1.
[4] T. Fujii et al., "16-Channel Membrane Directly Modulated Laser Array on Si for 2-km Transmission of 112-Gbps PAM-4," in Proc. ECOC 2023, paper We.B.4.1
[5] H. Nishi et al., "Integration of Eight-Channel Directly Modulated Membrane-Laser Array and SiN AWG Multiplexer on Si," JLT, **15**, 266-273 (2019).
[6] T. Fujii et al., "Multiwavelength membrane laser array using selective area growth on directly bonded InP on SiO_2/Si," Optica **7**, 838-846 (2020).