Efficient Modulation of InP-Based 1.3μm VCSELs with AsSb-Based DBRs

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Abstract— We demonstrate efficient, error-free 3.125Gb/s modulation of InP-based 1.3μm VCSELs with AsSb-based DBRs up to 60°C. These devices demonstrated high differential efficiencies (>60% at room-temperature), which resulted in a required bias current for modulation of only 5.9mA. The measured extinction ratios were greater than 8dB up to 60°C with a peak-to-peak drive voltage of only 800mV. The 3dB-down room-temperature small-signal bandwidth was 4.4GHz at a bias of 5.9mA.

***Index Terms*— Vertical-cavity surface-emitting lasers, semiconductor laser processing, modulation, InP-based, optical fiber communication, long wavelength, semiconductor lasers.**

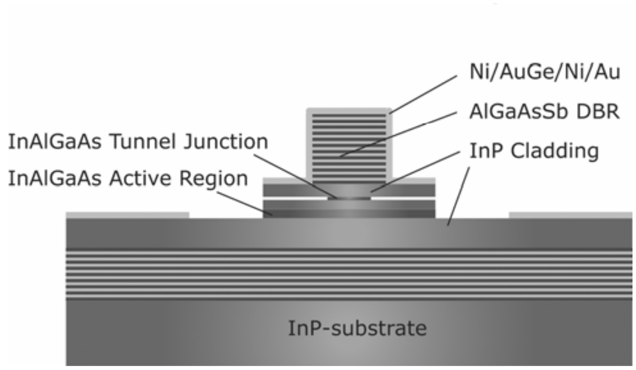

Fig. 1. Schematic of bottom-emitting all-epitaxial VCSEL structure with undercut tunnel-junction aperture.

I. Introduction

LONG WAVELENGTH vertical-cavity surface-emitting lasers (VCSELs) operating in the 1.3 – 1.6μm wavelength range are expected to provide a low-cost alternative to existing edge-emitting lasers in optical fiber communication systems. With low power consumption, on-wafer testing, and high fiber-coupling efficiency, VCSELs are attractive candidates for short to mid-range high data-rate applications such as CWDM, metro, and local area networks.

Much of the progress towards more manufacturable long wavelength VCSELs has been hampered by the necessity to match a reliable high-gain active region with high-index-contrast distributed Bragg reflectors (DBRs) over the full 1.3 – 1.6μm wavelength range. Approaches employing GaInAsN active regions have shown excellent characteristics near 1.3μm but still struggle to replicate that performance at higher wavelengths [1]. Wafer-bonded approaches have also shown promising results, but suffer from difficult processing steps [2]. A variety of methods employing the well-established InAlGaAs active region technology have perhaps shown the best performance [3,4,5]. Unfortunately, most of these approaches require a dielectric DBR and do not produce monolithic all-epitaxial devices, which is an important goal towards a more manufacturable product. Another approach is to utilize InAlGaAs active regions coupled with AlGaAsSb DBRs. InAlGaAs active regions are lattice-matched to InP and have demonstrated reliable high-gain operation over the full long-wavelength range with excellent temperature performance. AlGaAsSb DBRs are also lattice matched to InP and offer high reflectivity over a broad wavelength range, thus enabling wavelength selection from 1.3 – 1.6μm. In fact, the available index contrast is $\Delta n \approx 0.4$, comparable to that of the GaAs/AlGaAs system. Previously we have demonstrated excellent CW performance in devices employing AsSb-based DBR technology at both the important telecommunications wavelengths of 1.3μm and 1.55μm [6,7]. The feasibility of this technology for use in high data-rate applications, however, remains to be demonstrated.

In this letter, we report the first high-speed modulation of monolithic all-epitaxial 1.3μm VCSELs with AsSb-based DBRs. Modulation at a data rate of 3.125Gb/s was demonstrated and error free operation was obtained up to 60°C. These devices displayed high differential efficiencies, which resulted in a required bias current for modulation of 5.9mA. Open eye diagrams were observed at 3.125Gb/s up to 60°C. The extinction ratios were extracted and remain >8dB up to 60°C for a peak-to-peak drive voltage of only 800mV. Furthermore, excellent static characteristics were observed. The single-mode CW output power at room-temperature (RT) was >1.6mW and the differential quantum efficiency was 64%. The threshold current was 1.7mA and the lasing wavelength was 1.305μm with an SMSR of 46dB.

II. Device Structure and Fabrication

The VCSEL structure was grown monolithically in a single growth step by molecular beam epitaxy (MBE). Figure 1

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shows a schematic of the bottom-emitting VCSEL device. The device structure is the same as previously reported [7]. The ½-λ InAlGaAs multiple-quantum well active region is clad on both sides by InP layers. These layers facilitate current and heat spreading in the device and serve as intra-cavity contact layers, allowing for the circumvention of the high electrically and thermally resitive AsSb-based DBRs. The top and bottom DBRs are AlGaAsSb and AlAsSb and contain 39.5 and 25.5 pairs, respectively. Embedded within the upper InP cladding layer at a standing wave null is a 350Å n^{++}-InAlGaAs/p^{++}InAlGaAs tunnel junction layer that is selectively-etched to form a thin low-loss air-gap aperture. This aperture provides excellent optical and electrical confinement in the device [8,9].

Device fabrication consisted of reactive ion etching (RIE) of the top DBR down to the upper InP-cladding layer in Cl_2 plasma. Ni/AuGe/Ni/Au and SiO_2 were then deposited as the upper contact and etch mask, respectively. The upper InP cladding layer, which functions as an etch-stop layer for the upper DBR, was etched down to the tunnel-junction layer via RIE with CH_4-H_2-Ar. Selective lateral etching of the tunnel junction was then performed with a 10:1 mixture of citric acid and hydrogen peroxide to form the thin air-gap aperture. Subsequently, the remaining InP cladding was etched to the active region via RIE. Finally, the active region was etched in citric acid and hydrogen peroxide to expose the bottom InP contact layer. Ni/AuGe/Ni/Au was then evaporated to form the bottom contact.

III. Experiment and Results

Figure 2 shows the RT static light and voltage vs. current (LIV) characteristics for a 20μm VCSEL device with an 8μm diameter aperture. CW lasing was observed up to 88°C with a RT output power >1.6mW and a 64% differential quantum efficiency. These results represent new milestones for AsSb-based long-wavelength VCSELs. The threshold current was 1.7mA and the device lased single-mode at 1.305μm with an SMSR of 46dB. These devices were optimized for RT performance with a gain-mode offset of only 30nm. With a larger gain-mode offset, the maximum lasing temperature is expected to increase significantly.

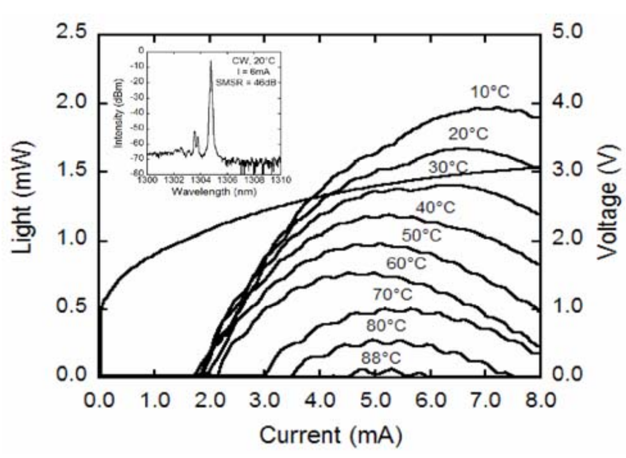

Fig. 2. CW LIV curves for bottom-emitting 1.3μm VCSEL with 8μm aperture for various stage temperatures. Inset lasing spectrum shows emission at 1.305μm and 46dB SMSR. Ripples on LI curve are due to substrate reflections from bottom-emitting device.

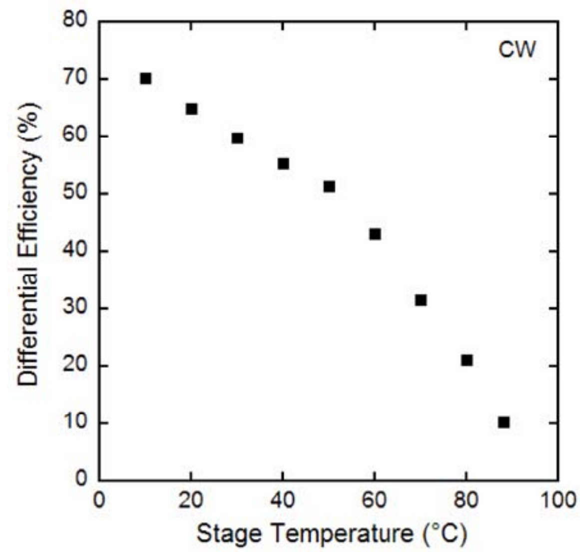

Fig. 3. CW Differential Efficiency vs. Stage Temperature showing differential efficiency of 64% at RT and over 50% at 50°C.

Figure 3 shows the CW differential efficiency vs. stage temperature for this device. The differential efficiency remained >50% up to 50°C. This result is an important advancement towards creating higher power devices with low required drive currents.

Figure 4 demonstrates the small-signal frequency response of the device at 20°C, 40°C, and 60°C. The maximum RT bandwidth was obtained at a bias of 5.9mA and is 4.4GHz. To illustrate the high-speed capabilities of these devices, the VCSELs were modulated using a 2^{31}-1 pseudorandom bit sequence (PRBS) at 3.125Gb/s up to 60°C. A signal

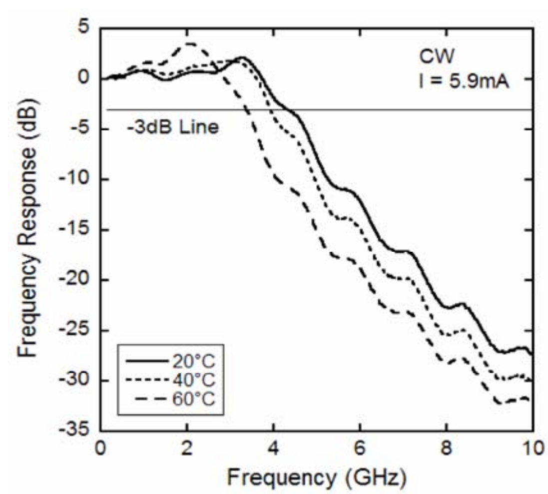

Fig. 4. Small-signal frequency response for VCSEL with 8μm aperture diameter at 20°C, 40°C, and 60°C at 5.9mA, 5.2mA, and 4.9mA drive currents, respectively.

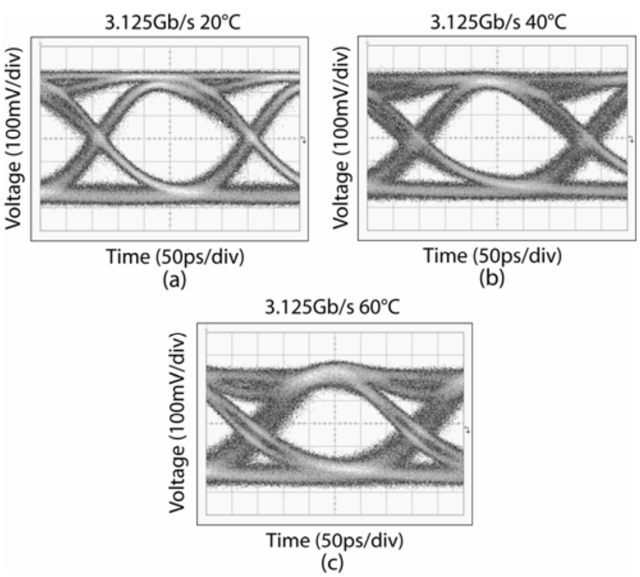

Fig. 5 Eye diagrams for 3.125Gb/s operation at 20°C (a), 40°C (b), and 60°C (c). Extinction is >8dB up to 60°C with a drive voltage of only 800mV.

generator and an error performance analyzer provided the data. Light was coupled directly from the device into standard single-mode fiber and then into a 10Gb optical receiver. Open eye diagrams were obtained up to 60°C. Figure 5 shows these results. The extinction ratios were derived directly from the optical bit stream and remained >8dB for operation up to 60°C with a peak-to-peak drive voltage of only 800mV. The bias currents at 20°C, 40°C, and 60°C were 5.9mA, 5.2mA, and 4.9mA, respectively.

In order to demonstrate the quality of the eye diagrams at 3.125Gb/s, bit-error rate (BER) measurements were performed in a back-to-back configuration. Figure 5 shows the BER vs. received power for 3.125Gb/s operation at 20°C,

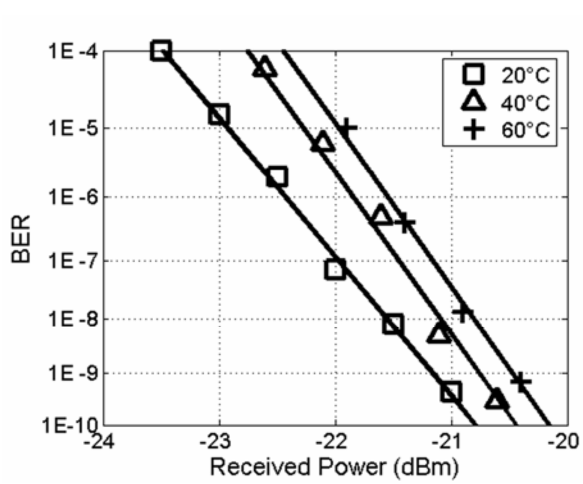

Fig. 6. BER vs. Received Power for 3.125Gb/s modulation at 20°C , 40°C, and 60°C for a 2^{31}-1 PRBS demonstrating error-free operation. Extinction ratio is >8dB up to 60°C. Measurements were performed back-to-back.

40°C, and 60°C. Error free operation was demonstrated for a 2^{31}-1 PRBS up to a temperature of 60°C. BERs below 10^{-9} were obtained, indicating that these devices are promising candidates for transmitters at a 3.125Gb/s data rate.

IV. Conclusions

We have demonstrated the first high-speed modulation for InP-based long wavelength VCSELs with AsSb-based DBRs. Error-free operation at 3.125Gb/s was demonstrated up to 60°C and open eye diagrams were obtained. The extinction ratios were >8dB up to 60°C with a peak-to-peak drive voltage of only 800mV. The high differential efficiencies demonstrated resulted in the low required drive voltages. These results clearly indicate the potential application of this all-epitaxial technology for high-speed data transmitters. Future work will involve larger gain-mode offset devices for improved temperature performance.

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