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All-Semiconductor Coupled-Cavity VCSELs for Narrow Linewidth

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***Abstract*—We demonstrate an all-semiconductor coupled-cavity VCSEL designed to achieve narrow linewidth at 850 nm. A resonant AlGaAs cavity of thickness 1,937 nm (8 wavelengths) is situated below the 3-quantum-well active region and results in an effective coupled-cavity length of 36 wavelengths.**

Keywords—VCSEL, Coupled Cavities, Linewidth, Frequency Noise, Single-Frequency Laser, Tunable Laser, Mode Selection, Atomic Clocks, Spectroscopy

I. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) have many desirable properties for low-power atomic clocks and spectroscopic sensors, such as low threshold current and single longitudinal mode operation.[1] However, due to the short effective cavity length (typically about 4 wavelengths), a VCSEL rarely achieves a linewidth less than 20 MHz.[2] Here we report on an all-semiconductor coupled-cavity VCSEL that achieves an effective cavity length of 36 wavelengths.

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II. VCSEL Design

A schematic drawing of the coupled-cavity VCSEL design is shown in Figure 1(A), where a passive 8-wavelength resonant cavity is located 4 periods below the active region. The passive cavity is composed of $Al_xGa_{(1-x)}As$ with x=0.16 that is doped n-type. Figure 1(B) shows the effective reflection coefficient from the passive cavity, as viewed looking down from the top of the 4-period middle distributed Bragg reflector (DBR).[3] Because the 8-wave passive cavity is resonant, the phase-shift versus frequency near the 850-nm resonance is equivalent to that of a 36-wavelength cavity that contains the active region.

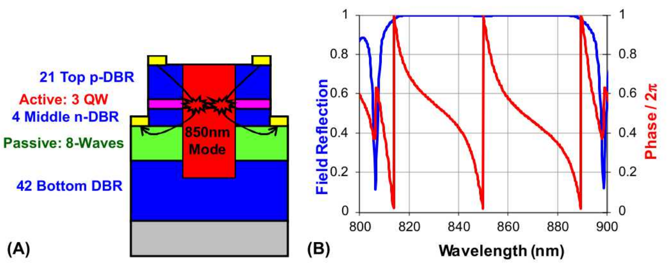

Figure 1: (A) Schematic drawing of the coupled-cavity VCSEL design, with a passive 8-wavelength cavity situated 4 periods below the active region. (B) Effective reflection coefficient looking down from the top of the 4-period middle DBR.

A transmission matrix simulation of the entire coupled-cavity VCSEL structure yields the reflection versus wavelength spectrum shown in Figure 2(A), which exhibits a cold-cavity linewidth of 34 pm. A conventional VCSEL with a 1-wavelength active region and a 21-period top DBR has a cold-cavity linewidth of approximately 210 pm, which is 6 times wider than that of the coupled-cavity VCSEL presented here. According to the Schawlow-Townes linewidth formula,[4-5] the lasing linewidth scales as the square of the cold-cavity linewidth, so we expect the coupled-cavity VCSEL to exhibit a lasing linewidth that is 36 times narrower than the conventional VCSEL linewidth of 40 MHz.[2] Figure 2(B) shows the measured reflection spectrum of the as-grown coupled-cavity VCSEL wafer, using a spectrometer of resolution 1 nm, which confirms the expected 38-nm free-spectral range of the passive coupled cavity.

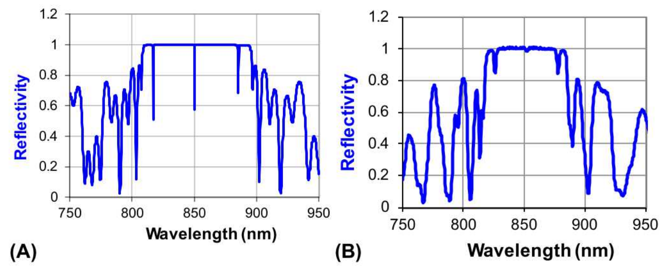

Figure 2: (A) Simulated reflection spectrum of the coupled-cavity VCSEL. (B) Measured reflection spectrum of the as-grown coupled-cavity VCSEL wafer.

The coupled-cavity VCSEL employs a thin-oxide aperture in the first DBR period above the active region.[6] Annular p-type and n-type ohmic contacts were applied to the top p-type DBR and the n-type passive cavity, respectively.

III. VCSEL Characterization

Figure 3(A) shows a microscope photograph of the coupled-cavity VCSEL lasing at 6 mA of drive current during probe-station testing. The diameter of the thin oxide aperture was 4.5 um for this device. The PI and VI data are shown in Figure 3(B), which indicates a threshold current of 3.4 mA, a peak output power of 1.2 mW, and a slope efficiency of 0.59 W/A.

The coupled-cavity VCSEL exhibited single-mode operation up to the maximum applied current of 8 mA. Figure 4(A) shows the single-frequency lasing spectrum at 6 mA drive current, measured with a resolution bandwidth of 0.1 nm. The side-mode spacing was approximately 0.35 nm and the side-mode suppression ratio was over 40 dB. Figure 4(B) shows

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tuning of the lasing wavelength versus temperature, measured at a constant drive power of 8 mW (near 4 mA of drive current). The measured temperature tuning coefficient of 0.062 nm/°C is consistent with our expectations, since the passive cavity tuning should dominate the coupled-cavity VCSEL tuning.

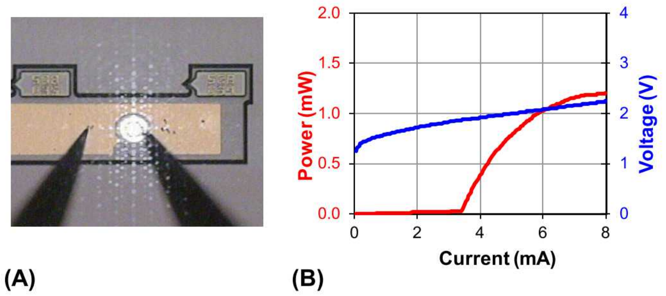

Figure 3: (A) Microscope photograph of the coupled-cavity VCSEL lasing at 6 mA of drive current. (B) PI and VI data from the same device showing a threshold current of 3.4 mA and a slope efficiency of 0.59 W/A.

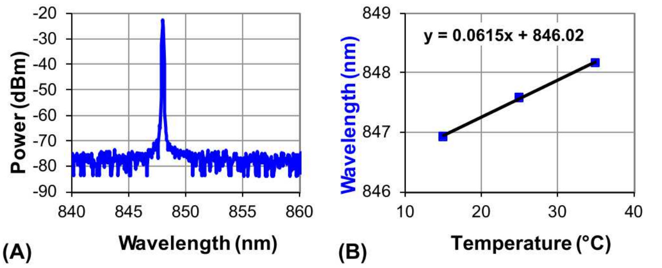

Figure 4: (A) Measured single-frequency lasing spectrum at 6 mA drive current. (B) Wavelength tuning versus ambient temperature from 15 to 35°C.

The measured threshold current of 3.4 mA at 23°C is about 4 times that of a conventional VCSEL having a 4.5-um aperture diameter and a 21-period output-coupling top DBR. In an effort to understand the cause of the high 3.4 mA threshold current, we added one additional dielectric DBR period by coating the top facet with a quarter-wavelength layer of silicon dioxide (SiO_2) and then a quarter-wavelength layer of silicon nitride (SiN), both deposited by plasma-enhanced chemical vapor deposition at 250°C.

After adding the additional dielectric DBR period, the simulated output coupling transmission decreased from 0.24% to 0.13%, and we measured the PI data shown in Figure 5(A), showing a decrease in threshold current from 3.4 to 3.15 mA, and a decrease in slope efficiency from 0.59 to 0.30 W/A. The decrease in threshold current of 7.4% corresponds to a reduction in transmission loss of 0.11%, indicating a total modal loss of 1.5% before adding the dielectric DBR period. If we assume a material loss of 10 cm^{-1} in the passive 8-wavelength cavity, then the effective reflection coefficient viewed from the active region is 0.985, indicating a loss of 1.5%, on par with our measurements. Hence, we conclude that the 3.4 mA threshold current is dominated by optical losses of approximately 10 cm^{-1} in the n-type passive cavity.[7] We plan to improve the coupled-cavity VCSEL performance by decreasing the optical losses in the passive cavity.

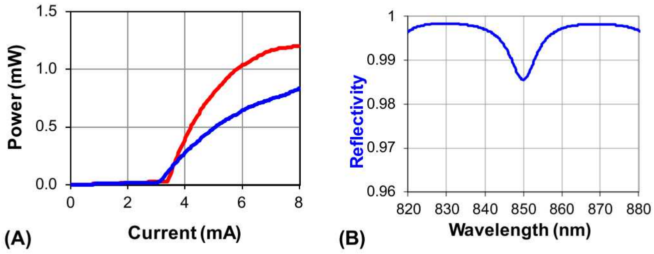

Figure 5: (A) Power versus current before (red) and after (blue) adding one additional dielectric DBR period, reducing threshold current from 3.4 to 3.15 mA. (B) Simulated effective reflection coefficient of the passive cavity, as viewed from the active region, showing a loss of 1.5% due to a material loss of 10 cm^{-1} in the passive cavity.

As a next step, we plan to measure frequency noise power spectral density to determine the intrinsic Lorentzian laser linewidth.[8]

IV. Conclusion

In summary we have fabricated and characterized an all-semiconductor coupled-cavity VCSEL that achieves an effective cavity length of 36 wavelengths, which is 12 times longer than the effective cavity length of a typical VCSEL. Material losses of approximately 10 cm^{-1} in the passive cavity dominate the 1.5% modal loss of the coupled-cavity VCSEL, limiting the potential linewidth narrowing to a factor of 36.

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