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High-Speed Vertical Cavity Surface Emitting Lasers*

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Abstract: High speed modulation and pulsing are reported for oxide-confined vertical cavity surface emitting laser diodes (VCSELs) with inverted doping and proton implantation to reduce the extrinsic limitations.

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We have previously demonstrated record modulation bandwidths for oxide-confined vertical cavity surface emitting lasers (VCSELs) based on strained InGaAs/GaAs quantum wells[1]. The monolithic oxide-confined structure[2] provides good optical confinement, low thresholds, efficient operation, and acceptable thermal resistance; these qualities promote high speed operation. Here we report work on nominally 850 nm wavelength oxide-confined VCSELs with modulation bandwidths in excess of 20 GHz.

High modulation bandwidths were achieved with an oxide confined VCSEL structure modified to decrease parasitic circuit elements. Figure 1 shows a schematic cross section of the VCSEL with a corresponding small signal equivalent circuit. Coplanar waveguide pads designed for on wafer probing were placed on a 5 μm thick polyimide to reduce the capacitance between the pad and the conducting substrate to approximately 50 fF. The device capacitance was further reduced by implanting the mesa area lying outside the active region. This was necessary due to the high capacitance of the thin oxide layer. The non-radiative recombination associated with the deep implant damage may also reduce the charge storage associated with diffusion underneath the oxide region. Finally, the sheet resistance of the upper mirror layer was reduced to $\sim 30 \Omega/\text{square}$ by making it n-type instead of the conventional p-up structure.

Figure 1. Schematic cross section of high speed VCSEL structure with superposed equivalent circuit.

The small signal response of VCSELs as a function of bias current was measured using a calibrated vector network analyzer with on wafer probing and a 30 GHz photodetector connected through approximately 2 m of the multimode fiber. Figure 2 shows the response of a single mode, $\sim 4 \times 4 \mu\text{m}^2$ laser with a 0.5 mA threshold current. The modulation response at various bias currents was fit with a traditional damped resonator model to extract the resonant frequency and equivalent damping frequency ($\gamma/2\pi$). These quantities for plotted in Figure 3 along with the -3dB

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bandwidth. At low bias currents, the bandwidth and resonant frequency increase in proportion to the square root of the current above threshold as expected from the conventional rate equation analysis. The rate of increase in this region yields a modulation current efficiency factor (MCEF) of 14.2 GHz/ $\sqrt{\text{mA}}$ which is slightly lower than the highest value we previously reported for oxide confined VCSELs with InGaAs quantum wells[1]. The resonant frequency increases steadily to 15 GHz at 2.7 mA and then becomes nearly constant. The -3dB bandwidth is as high as 21.5 GHz.

Figure 2. Frequency response of a VCSEL coupled to a high speed detector for various laser bias currents.

Figure 3. Resonance frequency (squares), -3dB frequency (circles), and equivalent damping frequency($\gamma/2\pi$) (triangles) as a function of square root of current above threshold.

Large signal, digital modulation experiments were also performed. Figure 4a shows the eye diagram during a 6 Gb/s test using $\sim 8 \times 8 \mu\text{m}^2$ multimode lasers with both drive levels above threshold. Bit error rates as low as 10^{-13} were observed in preliminary investigations at a data rate of 12Gb/s. Reducing the "0" level slightly below threshold resulted in substantial, pattern dependent jitter as seen in Figure 4b. Results for turn on delay, jitter, and other pulsed excitation experiments now in progress will be presented.

(a)

(b)

Figure 4. Eye diagrams generated by 6 Gb/s digital modulation of a multimode VCSEL at bias currents of (a) 7 mA and (b) 4 mA. In the latter case, the low drive level falls below threshold.

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[1] K. L. Lear et al., *Electron. Lett.* **32**(5), 457 (1996).

[2] K. D. Choquette et al., *Photon. Tech. Lett.*, **7**(11), 1237 (1995).