

uator section which is biased near the maximum extinction value. Fig. 4 shows the temporal trace of the pulse train at 3 GHz repetition rate. The FWHM pulse width is 39 ps under a driving power of 24 dBm, and the spectral width is 0.87 nm which is limited by the resolution of the spectral meter.

In summary, we have fabricated a novel compact tunable optical pulse generator by using a monolithic integrated MQW DBR laser/electro-absorption modulator. The bandgap energies of both the narrow-gap active MQW region and the wide-gap passive MQW region are controlled by the oxide width and grown at the same time using the selective-area epitaxy by MOVPE.

- [1] Wakita, Kotaka, Mitomi, Asai, Mikami, Kawamura, Naganuma, *J. Lightwave Technol.*, vol. 8, p. 1027, 1990.
- [2] Kato, Sasaki, Kida, Komatsu, Mito, *Tech. Dig. ECOC'91*, Paris, WeB7-2, 1991.
- [3] Aoki, Sano, Suzuki, Takahashi, Uomi, Takai, *Electron. Lett.*, vol. 27, p. 2138, 1991.

IIIB-7 Continuous Wave Visible InGaP/InGaAlP Quantum-Well Surface-Emitting Laser Diodes—K. F. Huang, K. Tai, C. C. Wu, and J. D. Wynn,* Department of Electro-Physics, Chiao Tung University, Hsinchu, Taiwan.

Vertical-cavity surface-emitting lasers at 0.66 μm visible spectral region were fabricated by metal-organic chemical vapor deposition technique. The continuous wave threshold currents I_{th} are 3.9 and 4.6 mA at -75 and -25 C, respectively, for 15 μm diameter devices. The lasers can also be operated at room temperature, but only in a pulsed mode with an I_{th} of 12 mA at 25 C.

Recently electrical injected visible vertical surface-emitting lasers (VCSEL's) have been reported with a pulsed threshold current of about 30 mA [1]. In this paper we report for the first time the continuous wave (CW) operation of such visible VCSEL diodes.

The laser structure studied here consists of four $\text{In}_{0.5}\text{Ga}_{0.5}\text{P}$ (80 \AA)/ $\text{In}_{0.5}\text{Al}_{0.35}\text{Ga}_{0.15}\text{P}$ (60 \AA) quantum wells as the active medium. The quantum wells are located in the middle of a one λ -thick cavity spacer, which is sandwiched between two highly reflective stair-case distributed Bragg reflectors (DBR's). Each period of DBR's consists of $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}/\text{Al}_{0.75}\text{Ga}_{0.25}\text{As}/\text{AlAs}/\text{Al}_{0.75}\text{Ga}_{0.25}\text{As}$ layers, with nominal layer thicknesses of 375, 100, 435 and 100 \AA , respectively. The top (bottom) DBR has 30 (40) periods and is Zn (Si) doped. Device processing steps include deposition of annular ring ohmic contacts, proton implantation, and chemical wet etching to isolate the devices.

Typical reflection spectrum of the InGaP/InGaAlP visible VCSEL wafer is shown in Fig. 1, which exhibits a square stop-band feature with the superposition of one sharp Fabry-Perot mode at 0.665 μm . Fig. 2(a) shows the typical cw light and voltage vs. current ($L-I$ and $V-I$) characteristics of the InGaP/InGaAlP visible VCSEL at various heat sink temperatures from -75 to -25 C. Sharp

thresholds in the $L-I$ characteristics are evident and occurs at 3.9 and 4.6 mA for -75 and -25 C, respectively. The $L-I$ slope efficiency and peak power at -75 C are about 0.28 mW/mA and 1.1 W, respectively. The $L-I$ curves are sub-linear and bent over at higher currents. The powers are completely quenched at even higher currents (not shown). However, the device does not show any damage at cw currents up to 25 mA, even at room temperature. Similar $L-I$ curves were observed and analyzed in previously studied 0.85 μm GaAs/AlGaAs VCSEL's having essentially the same gain-guided structure [2]. Fig. 2(b) shows the corresponding pulsed $L-I$ characteristics of the same laser at -70 to $+25$ C. The pulses are 300 ns wide and have a repetition rate of 10 kHz. Sharp thresholds in the $L-I$ characteristics are evident even at room temperature and occur at 6 and 12.5 mA for -70 and 25 C, respectively. It is interesting to note that the pulsed threshold currents at fixed temperatures are higher than the CW values. This thermal related phenomenon was also observed and analyzed in previously studied 0.85 μm GaAs/AlGaAs VCSEL's [2].

Fig. 3 shows the cw laser emission spectra at 2 (below threshold), 4 (near threshold) and 6 (above threshold) mA at -75 C. Single mode emission is evident in all spectra at about 0.66 μm wavelength. The inset of Fig. 4 shows the photograph of circular far field laser emission pattern. The far field emission angle (FWHM) is about 7.5° , which corresponds a near field spot size of 3.7 μm .

In conclusion we have fabricated visible gain-guided surface emitting lasers incorporating $\text{In}_{0.5}\text{Ga}_{0.5}\text{P}/\text{In}_{0.5}\text{Al}_{0.35}\text{Ga}_{0.15}\text{P}$ quantum wells $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}/\text{AlAs}$ DBRs. CW operation was achieved for temperature up to -25 C with a low threshold current of 4.6 mA. Fine adjustment on layer thickness and optimization in the proton implantation steps may yield room temperature continuous operation.

*J. D. Wynn is with AT&T Bell Labs., Murray Hill, NJ 07974.

- [1] J. A. Lott, R. P. Schneider, and K. J. Malloy, "Electrical injected AlInGaP visible vertical cavity surface emitting lasers operating at the $n = 2$ quantum well transition," *Conf. Lasers and Electro-optics 1993*, postdeadline paper CPD3, May 6, Baltimore, MD.
- [2] G. Hasnain, K. Tai, L. Yang, Y. H. Wang, R. J. Fischer, J. D. Wynn, B. E. Weir, N. K. Dutt, and A. Y. Cho, "Performance of gain-guided surface emitting lasers with semiconductor distributed Bragg reflectors," *IEEE Quantum Electron.*, vol. 27, pp. 1377-1385, 1991.

IIIB-8 Low Threshold, Electrically Injected InGaAsP (1.3 μm) Vertical Cavity Lasers on GaAs Substrates—J. J. Dudley, D. I. Babic, R. Mirin, L. Yang,* B. I. Miller,** R. J. Ram, T. Reynolds, E. L. Hu, and J. E. Bowers, Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106.

We demonstrate for the first time electrically injected long wavelength vertical cavity lasers (VCL) employing the InGaAsP (1.3 μm) active regions fused to GaAs/AlAs mirrors on GaAs substrates. The lasers operate pulsed at