High-power low-noise VCSEL seed laser for fiber laser applications

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ABSTRACT

The properties of high-power and low-noise seed lasers are key for high performance master oscillator-power amplifier (MOPA) fiber-lasers. We have successfully demonstrated high-power and low-noise seed lasers using our VCSEL technology. We used an external-cavity configuration with optimum cavity design for single-mode control, and the mode-beating problem can be fully avoided compared to the edge-emitter seed lasers. The external-cavity VCSEL achieved high-power single-mode pulsed operation with good mode quality that allowed it to be efficiently coupled into a single-mode PM or non-PM fiber. Using high-speed driving electronics, optical pulse widths of 12ns and shorter were obtained with repetition rates of up to 1 MHz. The optical output peak power obtained is over 10 W.

We have also demonstrated a CW version of this high-power VCSEL seed laser achieving single transverse and longitudinal mode with an output power of greater than 0.5 W. The high-power external cavity VCSELs were operated in single longitudinal mode demonstrating narrow spectral line-width of 200kHz, and having very low RIN of –155 dBc/Hz at 1MHz, which was even lower at higher frequencies.

Key words: Semiconductor lasers, vertical-cavity surface-emitting lasers (VCSELs), seed laser, low noise laser, pulsed fiber laser, brightness, reliability, single-mode operation

1. INTRODUCTION

Seed lasers are key components for high performance master oscillator-power amplifier (MOPA) fiber lasers, and studies showed how its parameters affect the fiber laser performance [1]. Several types of the semiconductor seed lasers have been developed for the MOPA fiber laser systems, based on edge-emitting distributed feedback (DFB) lasers and Fabry-Perot lasers. However, those edge-emitting diode lasers have some limitations for the pulsed fiber lasers, such as the slow pulse response and low single mode power, or otherwise incorporating a tapered laser or amplifier portion in the seed laser module to boost its power. Basically, a seed laser in a MOPA fiber laser system affects the fiber laser's spectral line width, noise, pulse parameters, and wavelength tuning, etc., compared to the DBR-type fiber lasers. A high-power seed laser can also eliminate the pre-amplifier stage(s) for simplicity and lower cost.

In VCSELs, single-mode operation is generally possible for small diameter devices, and is typically limited to a few mW of power [2]. To improve the single-mode power of VCSELs, an external-cavity configuration can be used in which a longer distance between the device and the external mirror forces it into a single-mode operation [3]. In this scheme, much larger VCSEL apertures can be used, and therefore much higher single-mode powers can be obtained. Several previous researches using either optical injection (pumping) [4] or direct electrical injection [5][6] have successfully demonstrated this approach. There are many advantages to single mode VCSELs which include low-cost manufacturing[7] and high reliability [8].

Our approach for electrically-injected external-cavity VCSEL was described in detail in references [9][10]. In order to achieve strong coupling to the external cavity, the middle mirror reflectivity is reduced, so that the VCSEL cannot lase without an external mirror. The external mirror consists of a flat piece of glass with a reflective coating on the external cavity side and an anti-reflection coating on the output side [10]. A curved mirror can also be used [9]. Diffraction and

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spatial filtering in the external cavity are controlled by the VCSEL/external-mirror distance and provide high-order mode suppression. Also, a larger fundamental mode than could be achieved with a standard, small-aperture self-lasing single-mode VCSEL device is produced and the ability to thus increase the size of the fundamental mode enables higher single mode powers. A similar approach was later used in [11] using a coated GRIN lens as the external mirror to further increase the spatial filtering effect.

Our high-power and low-noise single-mode seed laser at 1064nm is based on our newly developed large-aperture, and high-power VCSEL devices with nearly-diffraction-limited beam quality, low RIN, and no mode-beating, as well as fast pulse response, which is ideal for this high performance seed laser applications. Besides fiber amplifiers, this seed laser can also be used in many other applications, such as spectroscopy, and sensing, etc.

2. DEVICE AND EXPERIMENTAL SETUP

2.1 Device structure & fabrication

For high-power operation, efficient heat-removal is required and therefore a junction-down, bottom-emitting structure is preferred to improve current injection uniformity in the active region and to reduce the thermal impedance between the active region and the heat-spreader [12] [13]. A schematic of the structure without the heat-spreader is shown in Figure 1.

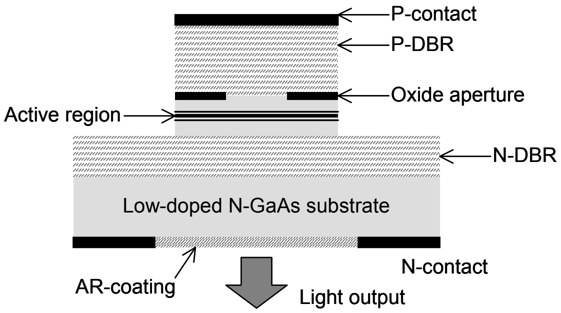


Figure 1. Schematic of the selectively oxidized, bottom-emitting 1064nm VCSEL structure.

For current and optical confinement, the selective oxidation process [14] is used to create an aperture near the active region to improve performance [15]. A low-doped GaAs N-type substrate is used to minimize absorption of the output light while providing electrical conductivity for the substrate-side N-contact. The growth is performed in a MOCVD or MBE reactor and starts with an AlGaAs N-type partially reflecting distributed Bragg reflector (DBR). The active region consists of InGaAs quantum wells designed for 1064nm emission and strained-compensated using GaAsP barriers [16]. The active region is followed by a high-reflecting P-type DBR. A high-Aluminum content layer is placed near the first pair of the P-DBR to later form the oxide aperture. The placement and design of the aperture is critical to minimize optical losses [17] [18] and current spreading [19]. Band-gap engineering (including modulation doping) is used to design low-resistivity DBRs with low-absorption losses [20].

The processing of bottom-emitting single devices is straightforward. On the epitaxial side, Ti/Pt/Au disks of different diameters are evaporated to form the P-type contacts, which at the same time act as the self-aligned mask for subsequent dry-etching (RIE) of mesas, deep enough to expose the Aluminum-rich layer. The samples are then exposed to high humidity in a furnace (390~420^{o}C) for the selective oxidation process. On the substrate side, the substrate is thinned to minimize absorption losses and then polished to an optical finish. A Si_3N_4 anti-reflection coating is deposited using PECVD, followed by patterning, etching of the field nitride and finally Ge/Au/Ni/Au N-metals evaporation. Finally, the devices are cleaved and packaged on heat-spreader submounts for testing.

2.2 The experimental setup

The setup is shown in Figure 2. Both CW and pulsed seed laser have similar setup except the cavity parameters, component specs, and driving electronics.

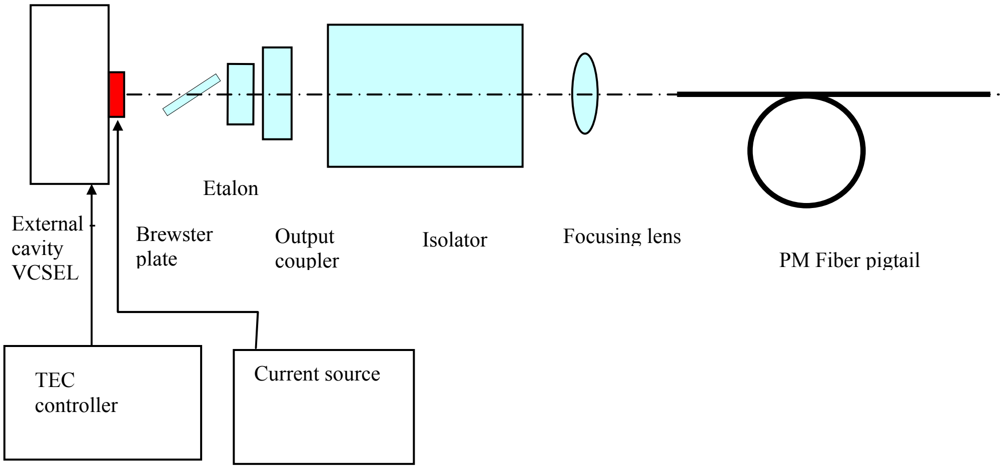


Figure 2. A general experimental setup for pulsed and CW seed lasers.

The Optical aspect of the setup: the external-cavity laser consists of VCSEL device and an output coupler. A high-quality Etalon and a Brewster plate in the cavity control the single-wavelength operation and linear polarization, respectively. The optical isolator prevents optical feedback from outside of the cavity to maintain the single-wavelength operation. The beam is then coupled into a PM fiber with a focusing lens for the mode matching.

The electrical aspect of the setup: the VCSEL on a sub-mount is temperature-controlled at 20°C; a DEI pulsed current driver is connected to the VCSEL through a strip line, pulse setting by an Agilent 33250A function generator, at pulse-width of 12nsec., and repetition rate range from 1kHz to 1MHz. The peak forward current is measured through its current monitor port with an oscilloscope. Also, the optical pulse width is measured by a fast and reversely-biased Silicon detector from Thorlabs, Model #DET10A, with about 1nsec rise time. The current and optical pulse traces by a Tektronix 500MHz oscilloscope are shown in Figure 3. The current monitor port is very noisy to see real current shape due to the DEI's driver's issue. We have a similar setup for CW operation, with an ILX CW laser diode driver to replace the DEI's pulsed driver.

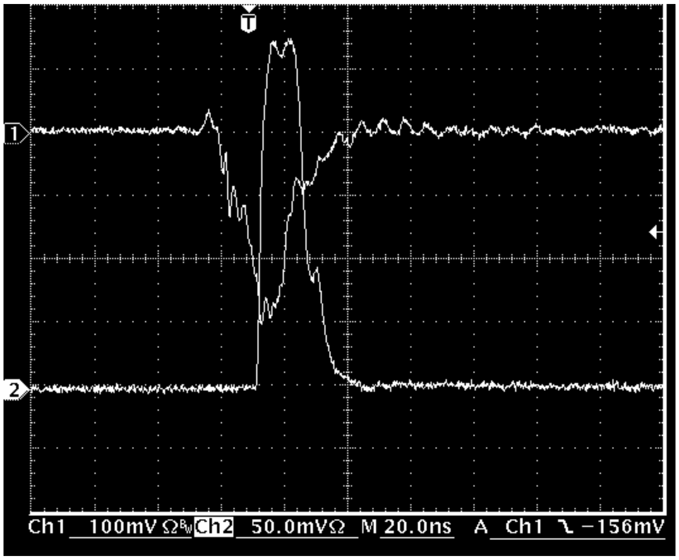


Figure 3. Electrical and optical pulse shape traces on an oscilloscope. Ch 1 is the Electrical pulse from the pulse driver's current monitor port, and the Ch 2 is the optical pulse measured at the laser's output by a fast Silicon detector.

3. RESULTS AND DISCUSSIONS

In this section, we present our measurement results, include both the pulsed and the CW seed lasers.

3.1 Pulsed seed laser

The LI curve with 17W peak power at the PM fiber output is achieved, shown in Figure 4. The peak power is calculated through the averaged power measurement with an Ophir thermopile power detector and the given duty cycle and pulse width to convert to peak power. Adding an isolator, the peak power is greater than 10W.

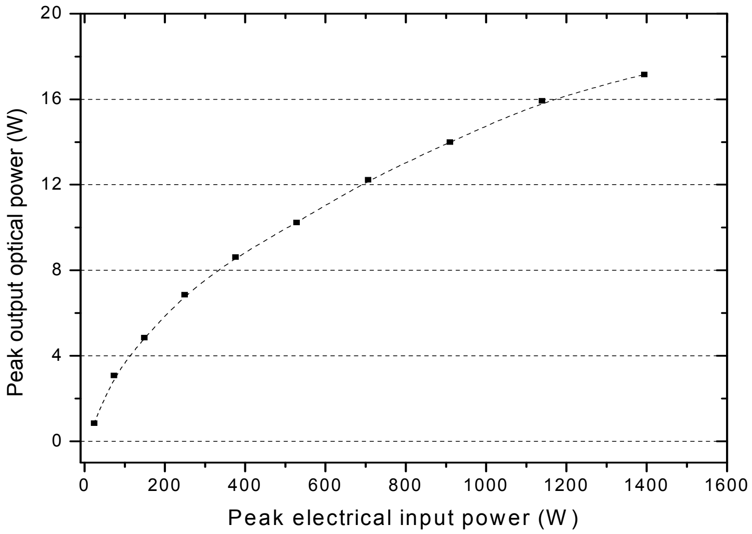
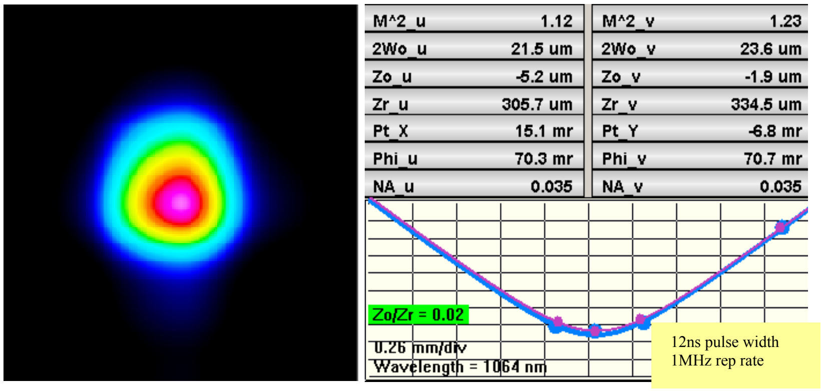


Figure 4. The LI curve of our pulsed seed laser.

The beam profile is measured, at the output of the output coupler before the isolator and PM fiber input, using a DataRay slit beam profiler and a good doublet lens, and the M^2 readout through the beam profiler's program (Figure 5.). Note that the beam profiler has only four plane scanning slits, and therefore the accuracy may not be as high as recommended by the ISO 11146 standard, but good enough for cavity tuning with M^2 monitoring; and also the laser is operating in pulse mode, the repletion rate must be high enough to get reliable readings from scanning-slit-type beam profiler. Here we used 1MHz repetition rate at about the maximum output power operation. The beam looks circular, single transverse mode with M^2 ~ 1.1 – 1.2 in two transverse directions.



M^2_u	1.12	M^2_v	1.23
2Wo_u	21.5 um	2Wo_v	23.6 um
Zo_u	-5.2 um	Zo_v	-1.9 um
Zr_u	305.7 um	Zr_v	334.5 um
Pt_X	15.1 mr	Pt_Y	-6.8 mr
Phi_u	70.3 mr	Phi_v	70.7 mr
NA_u	0.035	NA_v	0.035

Zo/Zr = 0.02
0.25 mm/div
Wavelength = 1064 nm

12ns pulse width
1MHz rep rate

Figure 5. Laser beam profile and M^2 estimate at the output coupler.

The laser's spectrum reveals a few longitudinal modes and the spectral envelope width is around 0.1nm when an Etalon is inserted into the cavity, fine-tuning the cavity to get side mode suppression > 10dB, or improve the Etalon, we can fully avoid the mode-beating problem which exists in the edge-emitter based seed lasers and could cause optical damage in the optics. Without the Etalon, the spectrum envelope width could be widened to around 0.5nm.

3.2 CW seed laser

Figure 6. shows the CW LI curve at the output of the output coupler, about 915mW, with good M^2 of about 1.1 in the two transverse directions, and the beam profile looks better than that in the pulsed seed laser's shown in Figure 6. The power at the PM fiber output is above 500mW. The maximum single-mode power reaches 915mW, and remains TEM00 mode operation (Figure 7). The line-width is too narrow to be measured by an Advantest optical spectrum analyzer with 0.01nm bandwidth, and we have estimated it to be around 200kHz using the self-heterodyne method.

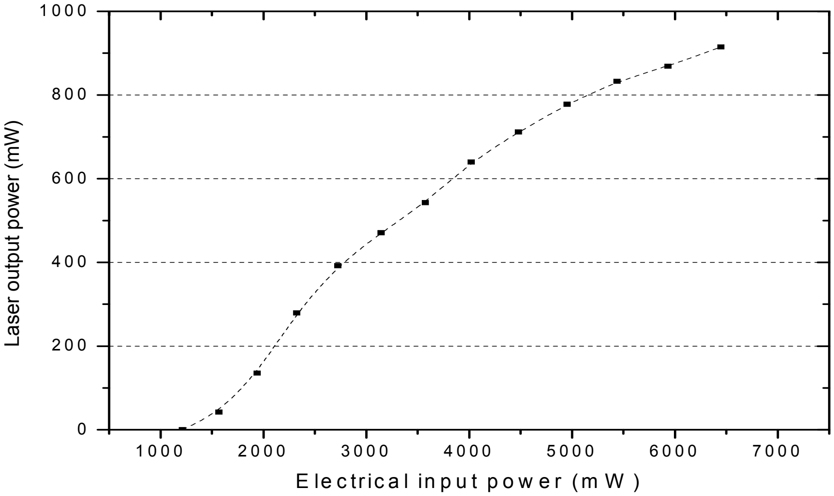


Figure 6. LI curve of the CW seed laser.

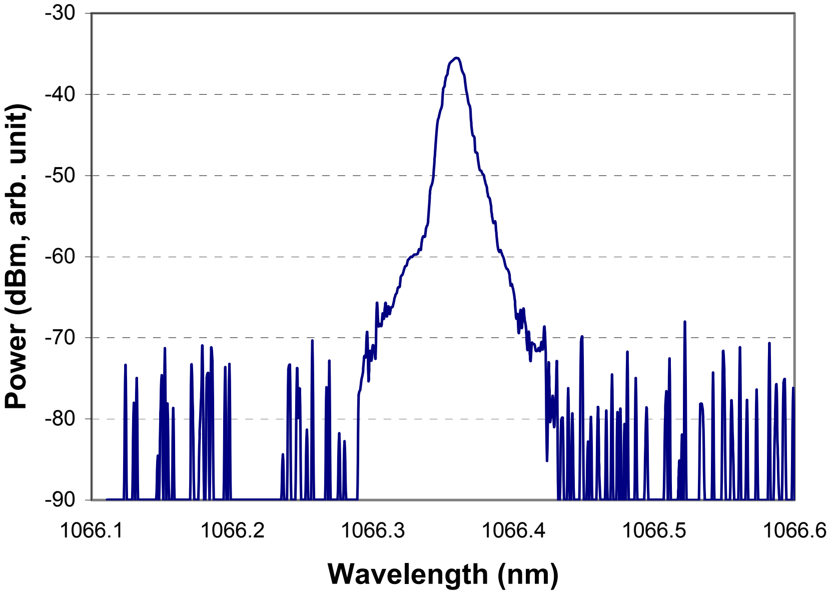


Figure 7. The optical spectrum at the CW seed laser output.

This laser has achieved very low RIN, about –155dBc/Hz at 1MHz, and even lower at higher frequency up to 1GHz range (Figure 8). The optical detector is an Applied Optoelectronics PD3000-FA-10-H-B, operating with detector current ~10mA giving shot noise limit of -165dBc/Hz; and two amplifiers from Mini-Circuits, one for low frequency range 100kHz to 500MHz, Model # ZFL-500LN, and the other 700MHz to 3.5GHz, Model #ZRL-3500+.

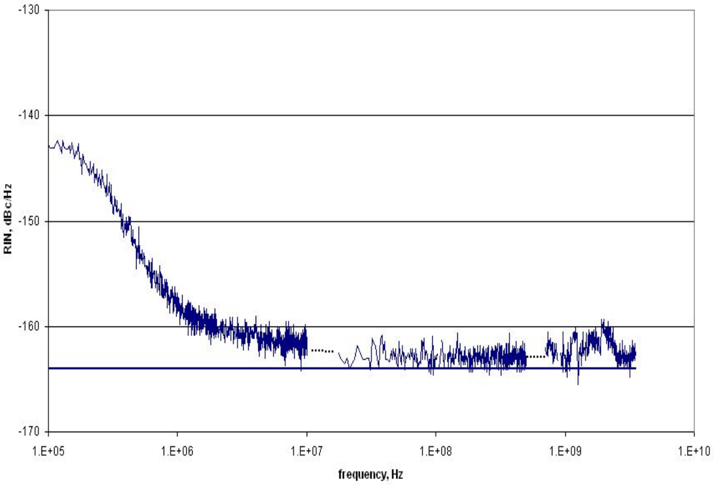


Figure 8. RIN measurement. The omitted data (dash line) around 10MHz is the electronics noise from the setup, not the optical noise from the laser.

4. CONCLUSIONS

We have successfully demonstrated our pulsed and CW seed lasers, and achieved our high-power and low-noise goals.

The pulsed seed laser has achieved the peak power of 17W at the PM fiber output, and the power of greater than 10W with an isolator, at 12nsec pulse width, and the pulse repetition rate range up to 1MHz. The optical spectrum envelope width at FWHM is around 0.1nm with the Etalon in the cavity, or, around 0.5nm without the Etalon.

The CW seed laser has achieved more than 0.92W laser output power with the single longitudinal mode, and more than 500mW PM fiber output. The RIN is measured < -155dBc/Hz at 1MHz and we achieved very narrow line-width of around 200kHz.

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REFERENCES

[1] Morasse, B., Chatigny, S., Gagnon, E., de Sandro, J.-P., and Desrosiers, C., "Enhanced pulseshaping capabilities and reduction of non-linear effects in all-fiber MOPA pulsed system," Proc. SPIE 7195, 1951D (2009).

[2] Grabherr, M.; Jager, R.; Michalzik, R.; Weigl, B.; Reiner, G.; Ebeling, K.J., "Efficient single-mode oxide-confined GaAs VCSEL's emitting in the 850-nm wavelength regime," *Photonics Technology Letters, IEEE* , 9(10), 1304-1306 (1997).

[3] Giudice, G.E.; Kuksenkov, D.V.; De Peralta, L.G.; Temkin, H., "Single-mode operation from an external cavity controlled vertical-cavity surface-emitting laser," *Photonics Technology Letters, IEEE* , 11(12), 1545-1547 (1999).

[4] Kuznetsov; M., Hakimi; F., Sprague, R., and Mooradian, A., "High-power (>0.5-W CW) diode-pumped vertical-external-cavity surface-emitting semiconductor lasers with circular TEM_{00} beams," *Photonics Technology Letters, IEEE* , 9(8), 1063-1065 (1997).

[5] Koch, B. J., Leger, J. R., Gopinath, A, Wang, Z., and Morgan, R. A., "Single-mode vertical cavity surface emitting laser by graded-index lens spatial filtering," *Applied Physics Letters* , 70(18), 2359-2361 (1997).

[6] Mooradian, A., "High brightness cavity-controlled surface emitting GaInAs lasers operating at 980 nm," *Optical Fiber Communication Conference and Exhibit, 2001. OFC 2001* , 4, PD17-1-PD17-3 (2001).

[7] Choquette, K. D., and Hou, H. Q., "Vertical-cavity surface-emitting lasers: moving from research to manufacturing," Proc. IEEE, 85(11), 1730-1739 (1997).

[8] Tatum, J. A., Clark, A., Guenter, J. K., Hawthorne III, R. A., and Johnson, R. H., "Commercialization of Honeywell's VCSEL technology," Proc. SPIE, 3946, 2-13 (2000).

[9] Hadley, M. A., Wilson, G. C., Lau, K. Y., and Smith, J. S., "High single-transverse-mode output from external-cavity surface-emitting laser diodes," Appl. Phys. Lett. 63, 1607 (1993).

[10] Wilson, G. C., Hadley, M. A., Smith, J. S., and Lau, K. Y., "High single-mode output power from compact external microcavity surface-emitting laser diode," Appl. Phys. Lett. 63, 3265 (1993).

[11] Koch, B. J., Leger, J. R., Gopinath, A., Wang, Z. and Morgan, R. A., "Single-mode vertical cavity surface emitting laser by graded-index lens spatial filtering," Appl. Phys. Lett. 70, 2359 (1997).

[12] Grabherr, M., Jäger, R., Miller, M., Thalmaier, C., Herlein, J., Michalzik, R., and Ebeling, K. J., "Bottom-emitting VCSEL's for high-CW optical output power," IEEE Photon. Technol. Lett., 10(8), 1061-1063 (1998).

[13] Michalzik, R., Grabherr, M., and Ebeling, K. J., "High-power VCSELs: modeling and experimental characterization," Proc. SPIE, 3286, 206-219 (1998).

[14] Dallesasse, J. M., Holonyak, Jr., N., Sugg, A. R., Richard, T. A., and El-Zein, N., "Hydrolyzation oxidation of $Al_xGa_{1-x}As$-AlAs-GaAs quantum well heterostructures and superlattices," Appl. Phys. Lett., 57(26), 2844-2846 (1990).

[15] Huffaker, D. L., Deppe, D. G., Kumar, K., and Rogers, T. J., "Native-oxide defined ring contact for low threshold vertical-cavity lasers," Appl. Phys. Lett., 65(1), 97-99 (1994).

[16] Hou, H.Q., Choquette, K.D., Geib, K.M., and Hammons, B.E., "High-performance 1.06-µm selectively oxidized vertical-cavity surface-emitting lasers with InGaAs-GaAsP strain-compensated quantum wells," *Photonics Technology Letters, IEEE* , 9(8), 1057-1059 (1997).

[17] Bond, A. E., Dapkus, P. D., and O'Brien, J. D., "Aperture placement effects in oxide-defined vertical-cavity surface-emitting lasers," IEEE Photon. Technol. Lett., 10(10), 1362-1364 (1998).

[18] Hegblom, E. R., Margalit, N. M., Fiore, A., and Coldren, L. A., "High-performance small vertical-cavity lasers: a comparison of measured improvements in optical and current confinement in devices using tapered apertures," IEEE J. Select. Topics Quantum Electron., 5(3), 553-560 (1999).

[19] Hegblom, E. R., Margalit, N. M., Thibeault, B. J., Coldren, L. A., and Bowers, J. E., "Current spreading in apertured vertical cavity lasers," Proc. SPIE, 3003, 176-180 (1997).

[20] Peters, M. G., Thibeault, B. J., Young, D. B., Gossard, A. C., and Coldren, L. A., "Growth of beryllium doped $Al_xGa_{1-x}As$/GaAs mirrors for vertical-cavity surface-emitting lasers," J. Vac. Sci. Technol. B, 12(6), 3075-3083 (1994).