# Single-Transverse-Mode Vertical-Cavity Lasers Under Continuous and Pulsed Operation

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***Abstract*—Using a hybrid ion implanted/selectively oxidized device structure, we report high-power single-mode operation of an 850-nm vertical-cavity laser. Under continuous-wave operation, >4 mW of single-mode power with 45 dB of side-mode suppression is achieved. The spectral behavior under pulsed modulation is determined to be influenced by thermal lensing. When biased to threshold, single-mode operation with >35-dB side-mode suppression is obtained for large signal modulation.**

***Index Terms*—Laser modes, modulation, vertical-cavity surface-emitting laser.**

## I. Introduction

SINCE the pioneering work on oxidation of AlGaAs [1] selectively oxidized vertical-cavity surface-emitting lasers (VCSELs) have been developed and have demonstrated high performance [2]. They typically lase in multiple transverse modes as a result of strong index confinement from the oxide layers. High-power single-mode operation is desired for a number of applications, including optical imaging and scanning, as well as data communication over single-mode fiber. A fundamental issue to obtain a single-mode VCSEL is that this usually requires reduction of the cavity cross-section area to decrease the number of transverse modes that are supported. However, this produces reduced active volume, which can substantially limit the output power of the fundamental mode. Moreover, VCSEL structures, which increase the loss of higher order modes often also increase the loss of the fundamental mode, albeit to a lesser extent. Therefore, demonstrating high-power fundamental mode emission from a VCSEL has to date been a challenge.

Techniques used to realize greater than 2-mW fundamental mode power from a VCSEL include, increasing the higher order mode loss by surface-relief etching [3] and extending the optical cavity [4], and by increasing the gain for the fundamental mode [5]. These prior demonstrations have characterized continuous-wave (CW) operation. In this letter, we report high-power single-mode operation from VCSELs employing both ion implantation and selective oxidation to define gain and loss regions in the optical cavity. This device structure allows us to increase the gain for the fundamental mode and increase the loss for higher order modes. We show the spectral characteristics of these VCSELs under CW and large signal modulation, and determine that thermal lensing is partially responsible for the single-mode operation of these VCSELs.

Manuscript received April 6, 2001; revised June 12, 2001.

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Publisher Item Identifier S 1041-1135(01)07547-4.

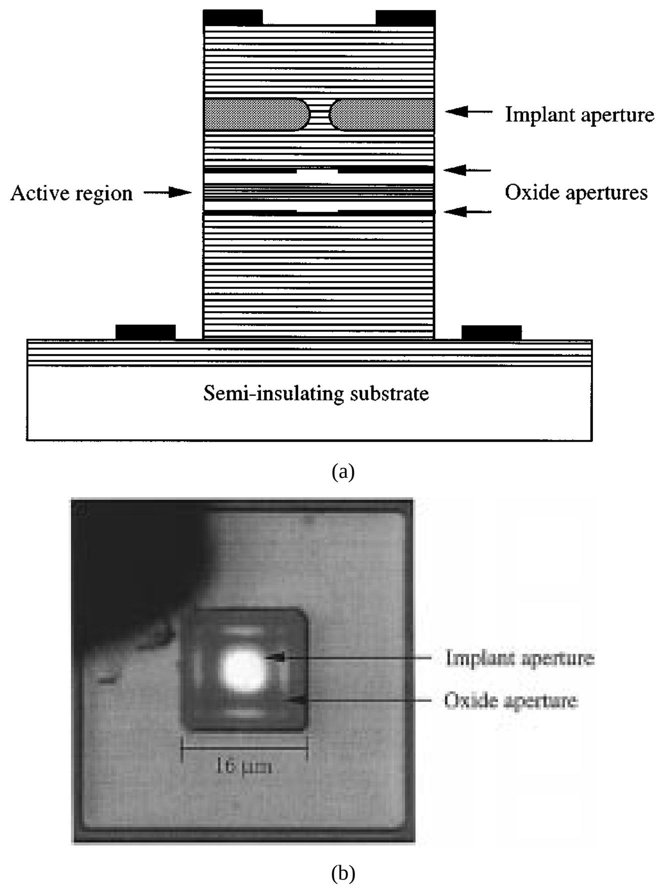
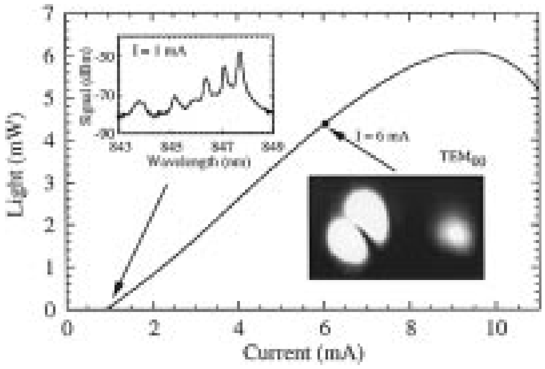


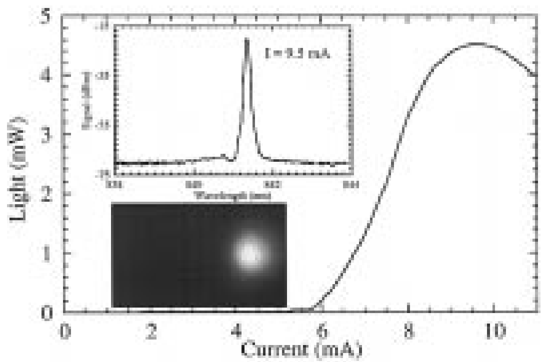

Fig. 1. (a) Side view sketch of hybrid implant/oxide VCSEL. (b) Top view image of VCSEL biased below lasing threshold showing presence of the implant and oxide apertures.

## II. Results and Discussion

The structure of the hybrid ion implanted/selectively oxidized VCSEL is shown in Fig. 1. By using two types of apertures in this device, we seek to decouple effects of the current confinement from the optical confinement. The implant aperture is used to confine the current flow, while the oxide aperture is used to confine the optical mode. The 850-nm VCSEL wafers are grown using metalorganic vapor phase epitaxy and have 21 and 35 mirror pairs in the top and bottom distributed Bragg reflectors (DBRs), respectively. A proton implant at 300 keV is performed




(a)




(b)

Fig. 2. CW light output, spectral characteristics, and near-field patterns for (a) VCSEL with a 6-$\mu$m implant diameter and $7\times7$ $\mu$m oxide aperture. (b) VCSEL with a 6-$\mu$m implant diameter and $9\times9$ $\mu$m oxide aperture. Both VCSELs were grown on a conducting n-type substrate.

to define conventional current apertures varying from 2 to 14 $\mu$m in diameter. Device mesas are then reactive ion etched and the samples are selectively oxidized to form the square optical apertures varying in size from 2 to 16 $\mu$m in length [2]. VCSEL wafers are grown on both semi-insulating and n-type substrates. For the former, the VCSELs are fabricated with concentric p- and n-type contacts (see Fig. 1), while for the latter, the VCSELs share a common backside n-type contact. The CW and pulsed spectral properties are measured using an HP 71451B optical spectrum analyzer. Spectrally resolved near-field mode profiles are obtained by illuminating the collimated laser beam onto a grating to spatially separate the modes, which are captured by a vidicon tube camera [6].

In Fig. 1(b), we show the top view of a VCSEL mesa biased below threshold. The round central light region corresponds to the smaller implant diameter (current aperture), while the outer square delineates the extent of the optical cavity (oxide aperture). Fig. 2(a) shows CW light output and spectral characteristics of a backside contacted VCSEL grown on a n-type substrate with an implant aperture of 6-$\mu$m diameter and an oxide aperture of $7\times7$ $\mu$m. The VCSEL emits over 6-mW peak power and exhibits multiple lasing modes throughout the current range of operation. The spectral response [inset in Fig. 2(a)] shows lasing in multiple transverse modes above lasing threshold. For this VCSEL, the spatially resolved near-field pattern at 6-mA bias in Fig. 2(a) shows the simultaneous presence of the fundamental mode and a higher order mode. These results indicate that in our structure, when the implant aperture is roughly the

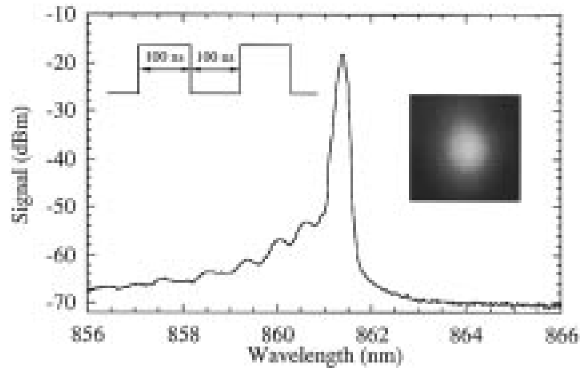


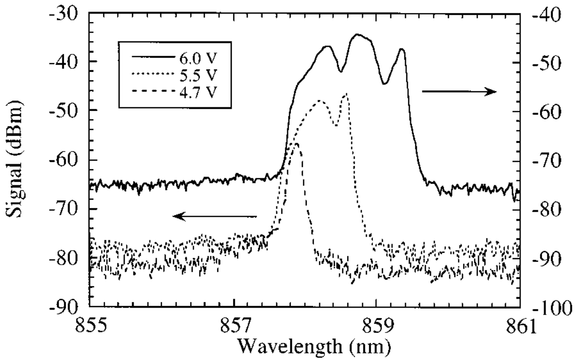

Fig. 3. Spectral response and near-field image of a hybrid VCSEL grown on a semi-insulating substrate under prebiased modulation at 3.2 V with a 6-$\mu$m implant diameter and an $8\times8$ $\mu$m oxide aperture.

same size as the oxide aperture, the spectral characteristics are essentially the same as expected from index-guided oxide-confined VCSELs [2].

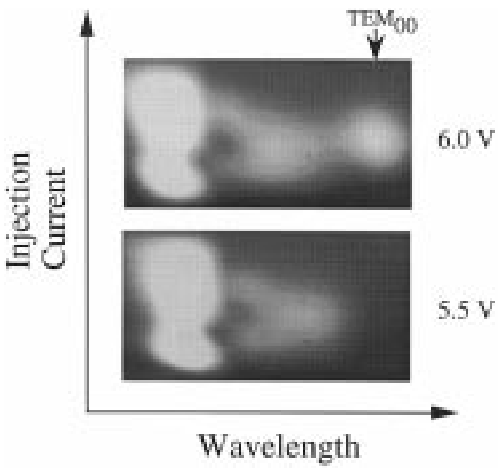
The CW light output and spectral response of another VCSEL on the same wafer with an implant aperture of 6 $\mu$m and an oxide aperture of $9\times9$ $\mu$m is shown in Fig. 2(b). Single-mode emission occurs from threshold to beyond the peak output power. The peak power reaches 4.5 mW and has a sidemode suppression ratio of over 45 dB. The near-field pattern confirms that only the fundamental mode is present over the full operation range. Increasing the oxide aperture diameter as compared to the implant aperture selectively funnels the injection current to the cavity center, and thus preferentially pumps the fundamental mode defined by the oxide aperture, while increasing the higher order mode loss, producing single-mode operation. The increased loss of the higher order modes, due to the unpumped quantum wells around the periphery of the implant aperture, while providing modal discrimination, also increases the threshold current as evident in Fig. 2(b).

To facilitate high-speed measurements, hybrid ion implanted/selectively oxidized VCSELs with coplanar probe pads are fabricated on semi-insulating substrates. Similar single-mode behavior, with peak powers of 3 mW or less, accompanied by increased threshold current is observed from these VCSELs. In order to better elucidate the mechanisms for single-mode operation in this hybrid implant/oxide device structure, pulsed measurements are performed on VCSELs grown on semi-insulating substrates with 6-$\mu$m diameter implant apertures and $8\times8$ $\mu$m-oxide apertures. The VCSELs are operated with 100 ns and longer pulses using an HP 8110A pulse generator and the output spectra, and modal profiles are simultaneously measured. Modulation to 3.4 V with a dc bias of 3.2 V is shown in Fig. 3. With the bias voltage set to threshold, fundamental mode operation with a sidemode suppression ratio of 35 dB is observed for 100-ns pulses, as evident from Fig. 3.

The modal characteristics observed under pulsed operation, but without the dc bias were found to differ dramatically. Fig. 4(a) shows the output spectra arising from three different modulation levels, and Fig. 4(b) depicts the corresponding near-field patterns for the two highest modulation levels. As shown in Fig. 4(a), as the modulation amplitude increases (with fixed pulsewidth), additional transverse modes arise




(a)




(b)

Fig. 4. (a) Spectral response and (b) near-field image for a VCSEL with a 6-$\mu$m implant diameter and an $8\times8$ $\mu$m-oxide aperture under pulsed voltage modulation with zero bias.

and begin to lase at a longer wavelength. As seen from the optical profiles in Fig. 4(b), the longer wavelength optical modes which begin to lase, are lower order than the initial lasing mode. Hence, under pulsed operation without a bias, the implant/oxide VCSELs tend to operate multimode, with the fundamental mode eventually appearing well above threshold. Repeating this measurement using longer pulses, we find as the pulsewidth is increased, the threshold lasing mode again shifts to the longer wavelength modes and ultimately to the fundamental mode.

We interpret the different modal evolution under modulation with zero versus nonzero bias as a manifestation of thermal lensing [7]. Prebiased modulation (Fig. 3) establishes a thermal lens, producing single-mode operation with large sidemode suppression ($>$ 30 dB) under pulsed operation. In the absence of a dc bias [see Fig. 4(a)], thermal lensing effects are not present and higher order modes reach threshold first due to preferential gain, presumably from current crowding effects. Note that current crowding will be exacerbated by the concentric contacts in the VCSELs grown on semi-insulating substrates, inspite of the small implanted current aperture. As the modulation amplitude or pulsewidth increases, more carriers are injected and diffuse to the center of the aperture, eventually creating a thermal lens. Finally, the high slope efficiency (2 W/A) observed with CW excitation in Fig. 2(b) is also consistent with the presence of a thermal lens in combination with a peripheral loss [8].

## III. Conclusion

Novel hybrid implant/oxide VCSELs are shown to emit high single-mode output power under CW and prebiased pulsed operation. We find the modal discrimination in these VCSELs is a combination of the periphery optical loss, on-axis current injection, and a thermal lens, all of which tend to support fundamental mode operation. High-power single-mode VCSELs, such as obtained using this hybrid ion implanted/selectively oxidized structure, will be beneficial for applications requiring high-speed modulation.

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