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Single Transverse Mode Selectively Oxidized Vertical Cavity Lasers

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Vertical cavity surface emitting laser (VCSEL) sources have been adopted into Gigabit Ethernet applications in a remarkably short time period. VCSELs are particularly suitable for multimode optical fiber local area networks (LANs), due to their reduced threshold current, circular output beam, and inexpensive and high volume manufacture. Moreover, selectively oxidized VCSELs [1] are nearly ideal LAN sources since the oxide aperture within the laser cavity produces strong electrical and optical confinement which enables high electrical to optical conversion efficiency and minimal modal discrimination allowing emission into multiple transverse optical modes. In addition to the large demand for multimode lasers, VCSELs which emit into a single optical mode are also increasingly sought for emerging applications, which include data communication with single mode optical fiber, bar code scanning, laser printing, optical read/write heads, and modulation spectroscopy. To achieve single mode selectively oxidized VCSELs is a challenging task, since the inherent index confinement within these high performance lasers is very large.

VCSELs typically have short (one wavelength long) optical cavities, and thus they inherently operate with a single longitudinal optical mode. However, because of their relatively large cavity diameter (roughly 5 to 20 μm), these lasers usually operate in multiple transverse optical modes. Each transverse mode possesses a unique wavelength and transverse spatial intensity profile. For applications requiring small spot size or high spectral purity, lasing in a single optical mode, usually the lowest order fundamental mode, is desired. Lasing only in the fundamental mode of a selectively oxidized VCSEL requires increasing the optical loss of higher order transverse modes as compared to that of the fundamental mode. Thus creating mode selective loss to increase modal discrimination will enable single mode VCSEL operation.

Recently at the VCSEL IV Conference held during the SPIE Photonics West 2000 Symposium in San Jose, CA, strategies for developing single mode VCSELs were discussed [2]. The proposals described either introducing relatively greater loss to higher order optical modes, or creating greater gain for the fundamental mode, and are sketched in Figure 1. Increased modal loss for higher order modes was demonstrated by three different techniques. The first approach utilized an etched surface relief on the periphery of the top facet as shown in Fig. 1(a), which selectively reduces the reflectivity of the top mirror for the higher order modes. An advantage of this technique is that the etched ring around the edge of the cavity in the top mirror can be accomplished either during VCSEL fabrication by conventional dry etching, as described by researchers at the University of Ulm, or can be post-processed on completed VCSEL die, as demonstrated by workers at the University of Bristol using focussed ion beam etching. A disadvantage of etched surface relief is that it requires careful alignment to the oxide aperture and can increase the optical scattering loss of the fundamental mode, as manifest by the relatively low (< 2mW) single mode output powers that have been reported.

It would be desirable to introduce mode selective loss into the VCSEL epitaxial structure to avoid extra fabrication steps and to provide a self-alignment. Two such techniques that were reported were the use of tapered oxide apertures and extended optical cavities within the VCSELs. The first approach pursued at Sandia is predicated on designing the profile of the oxide aperture tip to preferentially increase the higher order mode loss as sketched in Fig. 1(b). The aperture tip profile is produced by tailoring the composition of the AlGaAs layers which are oxidized to create the aperture within the VCSEL. As shown in Fig. 2, a VCSEL containing a tapered oxide whose tip is vertically positioned at a null in the longitudinal optical standing wave can produce greater than 3mW of single mode output with greater than 30 dB of side mode suppression. However, this structure requires a detailed understanding of the oxidation process and also produces additional loss for the fundamental mode.

Another way to increase modal discrimination is to extend the cavity length of the VCSEL as shown in Fig. 1(c) and thus increase the diffraction loss of higher order modes. Researchers at the University of Ulm reported single mode operation up to 5 mW using a VCSEL with a 4 μm thick cavity spacer inserted within the optical cavity. Using even longer cavity spacers introduced multiple longitudinal modes, but single transverse mode operation up to nearly 7 mW was demonstrated. It is interesting to note that VCSELs containing multiple wavelength cavities do not appear to suffer any electrical penalty, although careful design is required to balance the tradeoffs between the modal selectivity of transverse versus longitudinal optical modes.

Finally, manipulating the modal gain rather than loss can also produce single mode VCSELs. A technique to spatially aperture the laser gain independent of the oxide aperture has been developed at Sandia as sketched in Fig 1(d). The key aspect of these VCSELs is the lithographically-defined gain region which is accomplished by intermixing the quantum well active region at the lateral periphery of the laser cavity. The fabrication process begins with the growth of the bottom Bragg mirror and optical cavity which contains the quantum well active region. The active region is homogenized by ion implantation around masked regions which form the laser cavities. Following the quantum well intermixing, the top Bragg mirror is grown epitaxially. The resultant VCSEL has a central quantum well region which preferentially provides gain for the fundamental mode. Single mode output of more than 2 mW with side mode suppression ratio greater than 40 dB was obtained. Although this approach requires greater fabrication complexity, it is anticipated that higher performance can be attained with further refinement of the process parameters.

In summary, motivated by the new demands of emerging VCSEL applications, single mode VCSELs are presently under development at numerous laboratories around the world. The techniques demonstrated to date introduce modal discrimination by increasing the optical loss of the higher order modes, or by increasing the relative gain of the fundamental mode. The comparative merits of the various approaches are still being sorted out, where the criteria are the degree of increased fabrication complexity, tradeoffs to the overall laser performance, and maximum single mode output that can be achieved. Presently 5 mW represents the best single mode output from a VCSEL to date, whereas 10 mW or greater of single mode power would likely fuel the next generation of VCSEL applications.

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References

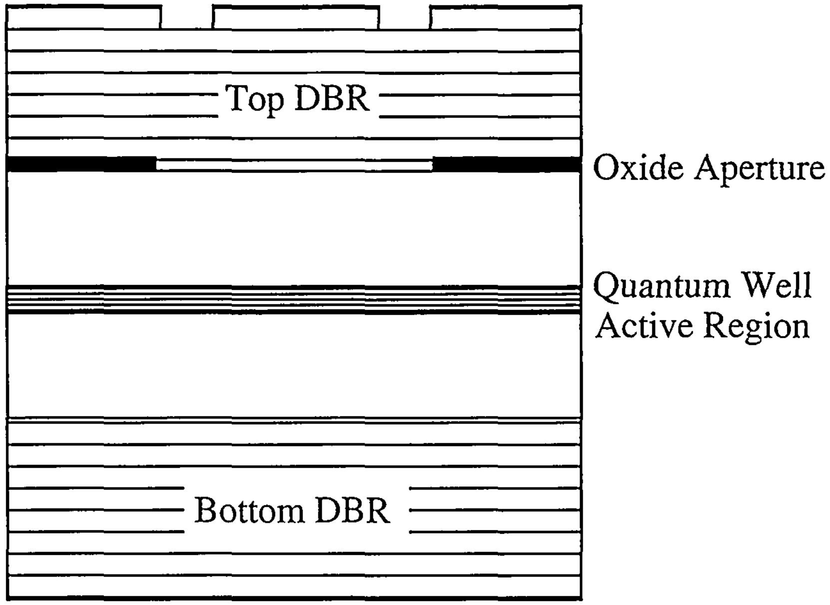
[1] Efficient Semiconductor Light-Emitting Device and Method, K. D. Choquette, K. L. Lear, and R. P. Schneider, Jr, U. S. Pat. No. 5,493,577 (Feb. 20, 1996).

[2] Proceedings of SPIE: Vertical Cavity Surface Emitting Lasers V, K. D. Choquette and S. Lei, Editors, Proc. SPIE **3946** (2000).

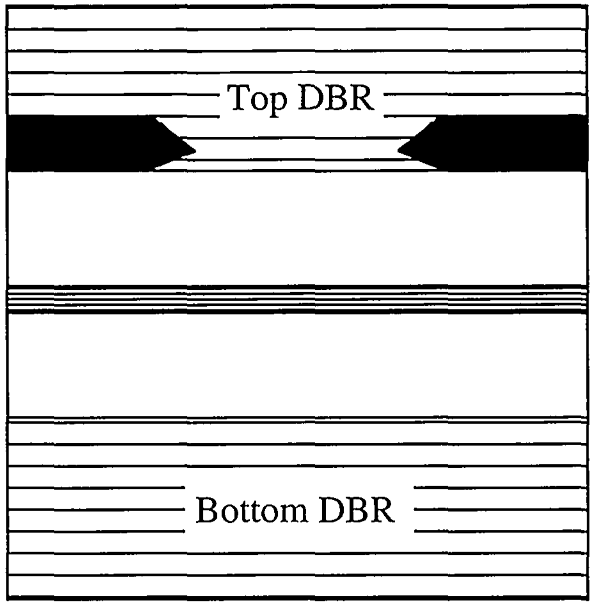
Figure Captions

Figure 1. Sketch of VCSEL structures pursued for single mode output power: (a) etched surface relief; (b) tapered oxide aperture; (c) extended optical cavity; and (d) gain apertured.

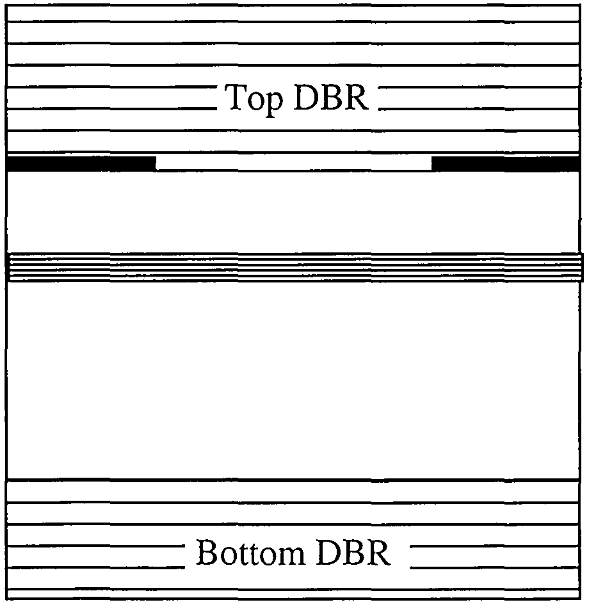
Figure 2. Single mode output power from a selectively oxidized 850 nm VCSEL containing a 4x4 μm tapered oxide aperture which produces >30 dB of side mode suppression at 3.5 mW.



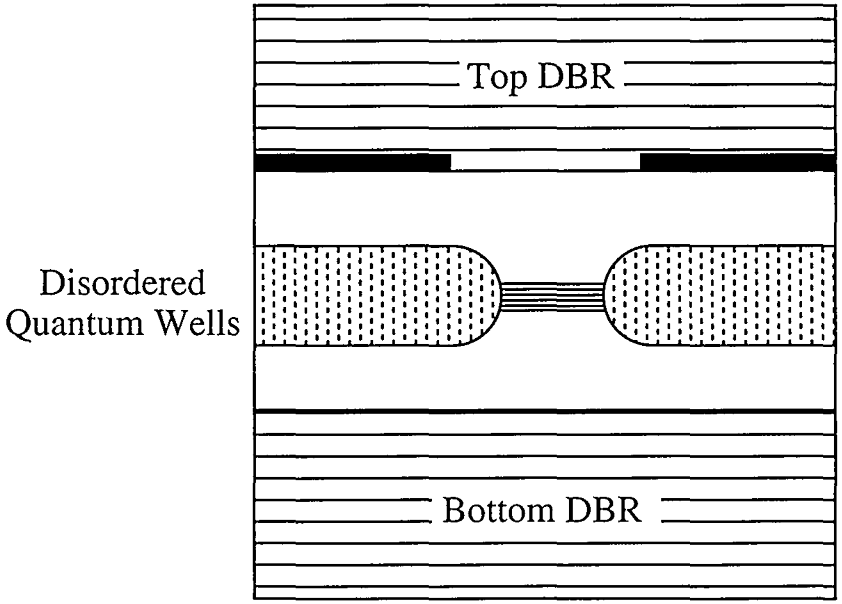
(a) DBR Surface Relief



(b) Tapered Oxide Aperture



(c) Extended Optical Cavity



(d) Gain Aperture

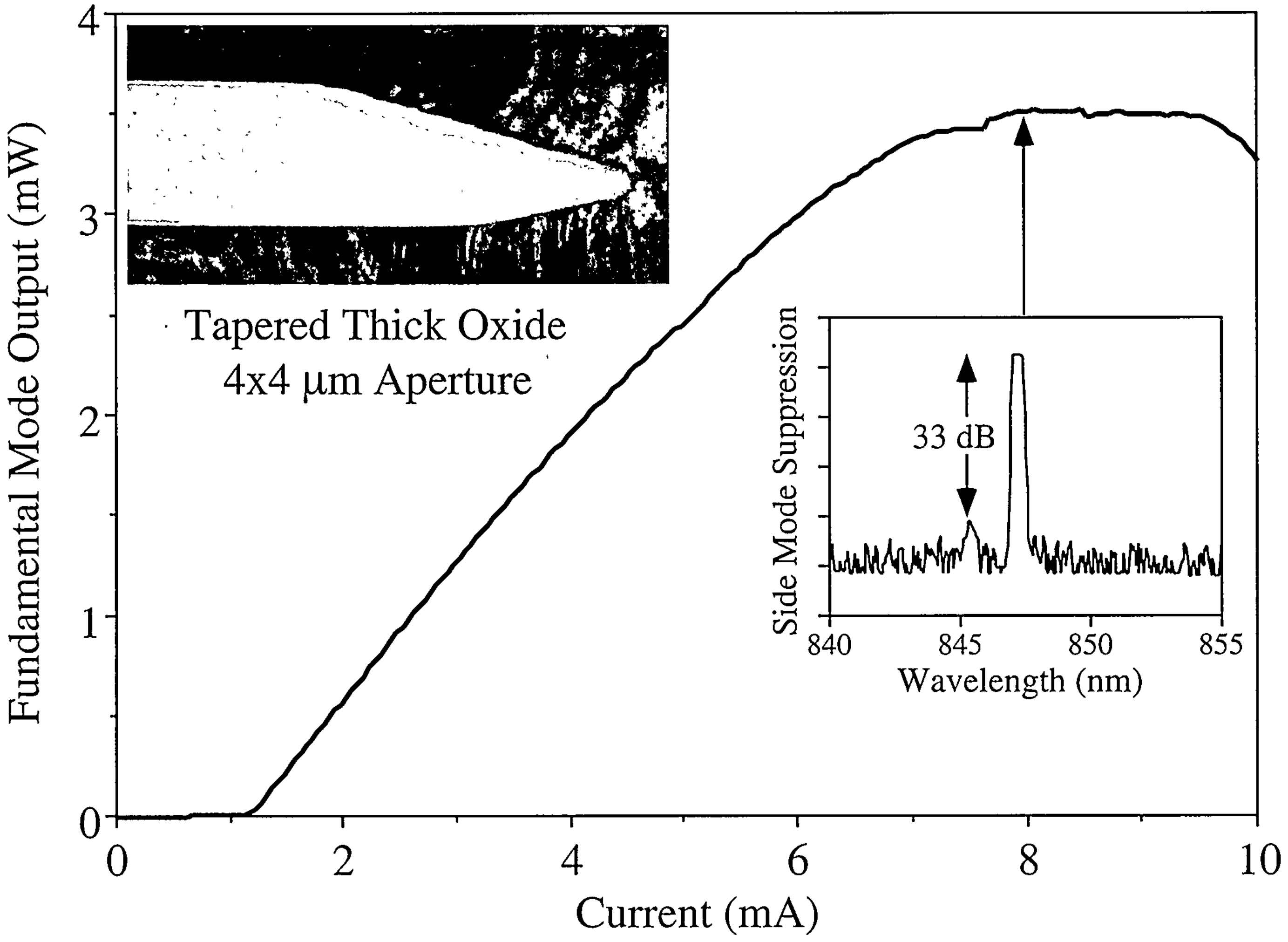

Fundamental Mode Output (mW)
0
1
2
3
4
0
2
4
6
8
10
Current (mA)
Tapered Thick Oxide
4x4 µm Aperture
Side Mode Suppression
33 dB
840
845
850
855
Wavelength (nm)

Figure 2