Scaling of small-aperture photonic crystal vertical cavity lasers

Aaron J. Danner, James J. Raftery, Jr., Uppiliappan Krishnamachari, Jason C. Lee,
Noriyuki Yokouchi*, Kent D. Choquette

University of Illinois at Urbana-Champaign, Urbana, IL 61820
**The Furukawa Electric Company, Ltd., Yokohama, Japan*
adanner@uiuc.edu

Abstract: Photonic crystal confinement incorporated into vertical cavity surface-emitting lasers (VCSELs) produces reduced excess loss as the aperture diameter decreases. The improved scaling enables a new topology of coupled vertical cavity lasers.

1. Introduction

One promise of microcavity lasers is the enhancement of performance as the optical resonator size decreases [1]. For example, if the threshold carrier density scales with the active volume, then laser operation can be expected at extremely low injection currents for very small laser cavities. An important technological example is the reduced threshold currents achieved with selectively oxidized vertical cavity surface emitting lasers (VCSELs) [2,3]. However, to date, every approach for reducing the VCSEL transverse cavity size has not produced a scalable threshold current, although advances in selectively-oxidized VCSELs have produced improved scaling [4]. We show for the first time that incorporating a photonic crystal cavity within a VCSEL can further improve the scaling of threshold current density for reduced cavity diameter beyond what is possible with oxidized VCSELs. This indicates the potential of this structure to achieve low threshold currents and helps enable a new topology of coupled vertical microcavity lasers.

2. Experimental Setup

Triangular-lattice photonic crystal holes were etched into the top facet of oxide-confined VCSELs as shown in Fig. 1 [5,6]. A centralized region where hole(s) are absent forms an area of increased effective index compared to its surroundings, forming an optical aperture. Photonic crystal lattice spacing varied between 1.8 and 5.8 μm, hole diameter to lattice spacing ratio varied between 0.5 and 0.7, and hole etching depth varied between 9 and 21 pairs of the top 25 periods of the distributed Bragg reflector. Optical apertures for photonic crystal VCSELs are approximately circular, the radius of which is taken as the distance from the center of the defect to the edge of the nearest etched hole. The effective threshold current densities for the photonic crystal VCSELs are calculated assuming uniform current injection through the larger oxide apertures [6]. Oxide aperture sizes ranging from 15 to 25 μm in length are used in order to minimize the larger refractive index contrast arising from the oxide, which permits operation in the photonic crystal mode rather than an oxide mode (see Fig. 1(a) and (c), respectively).

3. Results

Threshold current densities were measured for selectively oxidized VCSELs and photonic crystal VCSELs and appear in Fig. 2. For the oxide-confined VCSELs, the variation of threshold current density with aperture size follows the typical size dependence, and indicates the increased optical loss for small apertures [4]. Note the VCSEL wafer is optimized for reduced oxide aperture induced loss (thin oxide positioned three mirror pairs away from the active region). The effective threshold current densities for photonic crystal VCSELs (of a variety of photonic crystal designs) show a large degree of scatter in Fig. 2, although the lowest thresholds are equal to or lower than those of the oxide-confined VCSELs. For the photonic crystal VCSELs in Fig. 2 with the lowest threshold current densities, scaling is improved relative to that of the oxide-confined VCSELs. With advances in processing techniques of photonic crystal VCSELs, further improvements in the scaling observed here may be seen.

Embedding multiple ultra-small cavities could provide the infrastructure for novel vertical cavity photonic integrated circuits. An example of two adjacent photonic crystal cavities within a single gain region and their associated spectrum is shown in the near field image of Fig. 3. Note the coupling between the cavities should be influenced by the photonic crystal design, opening the potential for vertical cavity photonic integrated circuits. We conclude that photonic crystal VCSELs show the potential for achieving low threshold currents at small aperture sizes, enabling new design topologies for coupled vertical microcavity lasers.

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4. References

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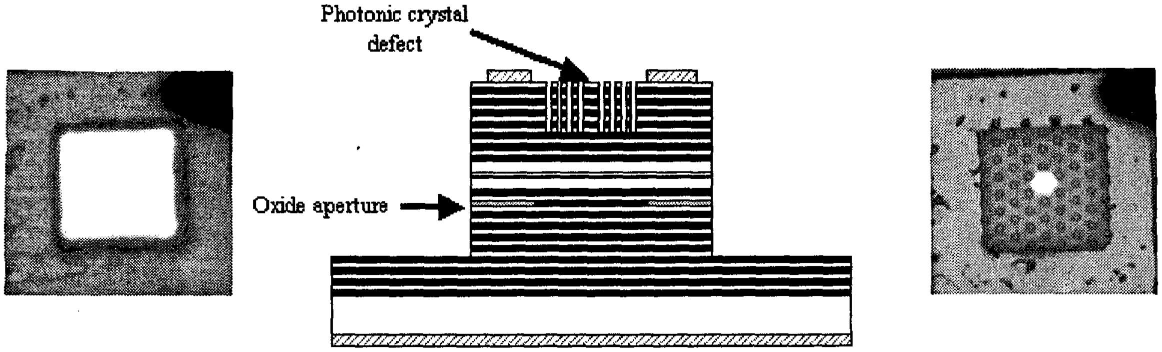

(a) (b) (c)

Fig. 1. (a) Oxide-confined VCSEL lasing above threshold; (b) Basic structure of a photonic crystal VCSEL. One, seven, or nineteen hole(s) absent from the center region create the optical aperture; (c) Photonic crystal VCSEL lasing in the fundamental lateral mode.

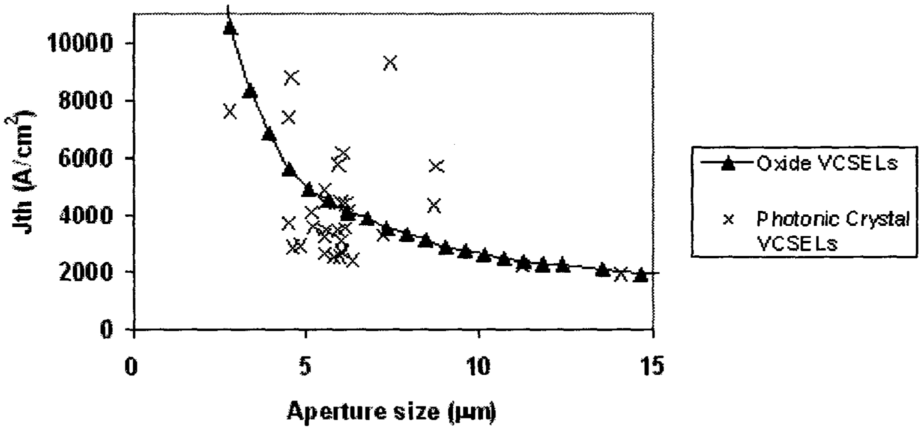

Fig. 2. Threshold current densities of various devices, all fabricated on the same VCSEL wafer, plotted versus aperture size.

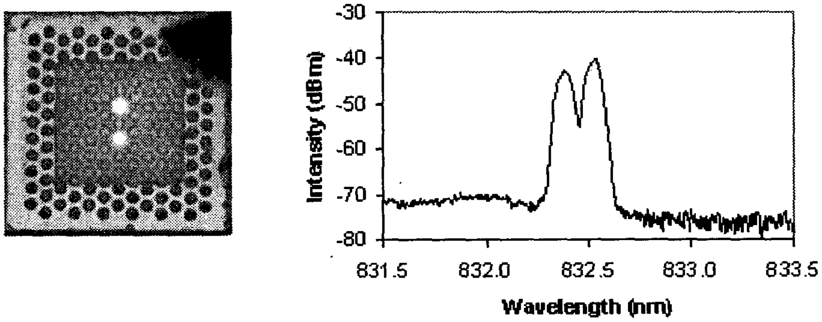

Fig. 3 Two adjacent photonic crystal cavities and their emission spectrum.