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A. J. Danner
University of Illinois at Urbana-Champaign

J. C. Lee
University of Illinois at Urbana-Champaign

James J. Raftery Jr.
United States Military Academy

Kent D. Choquette
University of Illinois at Urbana-Champaign

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Photonic Crystal Vertical Cavity Lasers

Aaron J. Danner, Jason C. Lee, James J. Raftery, Jr., and Kent D. Choquette*
University of Illinois-Urbana-Champaign, Urbana, IL 61801

ABSTRACT

Photonic crystal confinement in vertical cavity surface-emitting lasers (VCSELs) is a robust and reliable technology for achieving operation in the fundamental lateral mode and is potentially applicable to a variety of materials systems and operating wavelengths. We demonstrate photonic crystal VCSELs operating in a single transverse mode with over 30 dB side mode suppression and over 1 mW of output power. These lasers have been subjected to a post-process technique to introduce the etched holes making up the photonic crystals that surround a centralized defect in which lasing occurs. We also show that coupling between adjacent defects in a photonic lattice is possible, further increasing the power available in the devices.

Keywords: VCSEL, photonic crystal, transverse modes, single mode

1. INTRODUCTION

Operation of a vertical cavity surface-emitting laser (VCSEL) in the fundamental lateral mode is important for free space optical interconnects, data communication through single mode fiber, and modulation spectroscopy, for example. While established methods exist for achieving single mode operation in VCSELs, they typically involve small apertures or complex fabrication procedures. For example, selectively oxidized VCSELs give reliable single mode operation when the oxide aperture is under approximately 3 μm. However, achieving single mode selectivity for larger devices is very challenging because the lateral index confinement introduced by the oxidized layer is large. Altering the inherent index in a selectively oxidized VCSEL is not possible after fabrication is complete, and can only be modified slightly by changing the composition of the aluminum-containing oxide layer or altering the thickness [1]. Other methods of achieving single mode operation typically involve introducing loss into the VCSEL cavity that is selective to higher-order transverse modes, such as surface-relief etching [2].

Photonic crystal confinement is a method of introducing a very controlled lateral index change into a VCSEL cavity through the addition of small holes in the top distributed Bragg reflector (DBR) [3-6]. The holes are arranged such that they form a photonic crystal pattern that can be analyzed theoretically in frequency space with photonic band diagrams. Figure 1(a) illustrates the typical arrangement of circular etched holes surrounding a central defect region. Using the out-of-plane propagation vector as the abcissa in Figure 1(b), the allowed modes are plotted theoretically assuming infinitely deep holes; the diameter is 0.85 times the photonic crystal lattice constant. Only a limited number of guided modes are allowed; the rest are radiation modes. Two of the allowed guided modes for the structure shown are pictured in Figure 1(c). Through proper design of the photonic crystal pattern and consideration of the etching depth dependence, all guided modes except the fundamental can be eliminated [3,4]. Thus, in a photonic crystal VCSEL, the dispersion properties of the etched lattice lead to single mode operation, analogous to endlessly single mode operation in a photonic crystal fiber [7]. From a band diagram analysis, an effective index approximation is used to compare this confinement with other techniques. Figure 2 shows a cross section of a photonic crystal VCSEL utilizing an oxide aperture for electrical confinement and etched holes for lateral optical confinement. The index profile is approximated in this Figure to illustrate that the index step introduced by the photonic crystal can be designed to be much lower than that caused by the oxidized layer. This allows a larger optical aperture than is possible with single mode selectively oxidized VCSELs resulting in increased output power.

2. FABRICATION

One advantage of photonic crystal confinement is the simplicity of the fabrication method. The etched holes are typically added as a post-process step. A silicon dioxide dielectric mask is first deposited, and then selectively removed with focused ion beam etching in the correct photonic crystal pattern (or with dry etching following an

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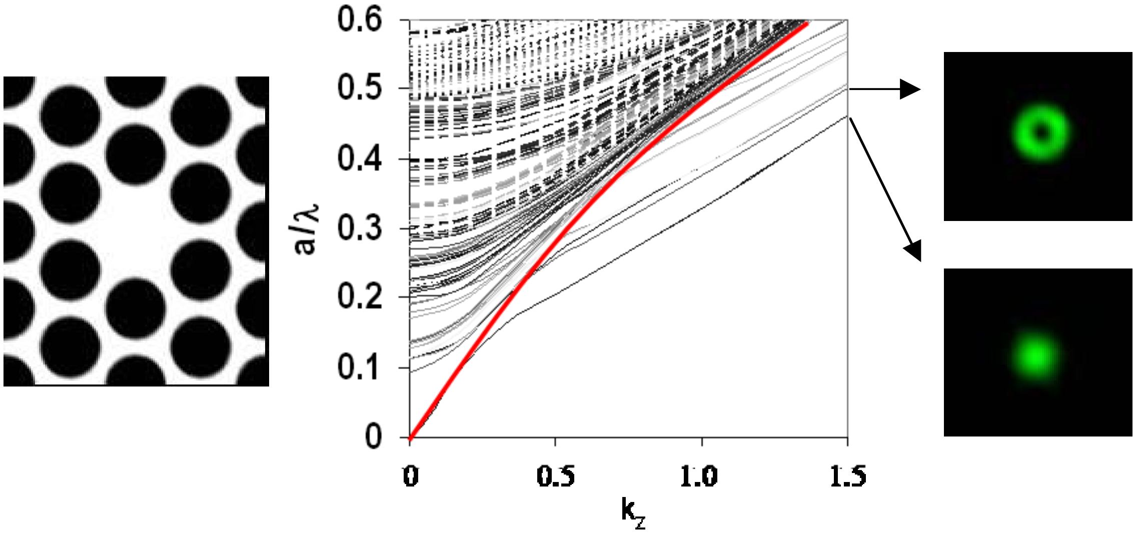

(a) (b) (c)

Figure 1. (a) Pattern of etched holes in VCSEL material; (b) Out-of-plane allowed modes. A 4x4 supercell was used in the plane wave calculation. Modes above and to the left of the solid line are radiation modes and those to the right and below are guided defect modes; (c) Two of the guided defect modes at $k_z = 1.5$

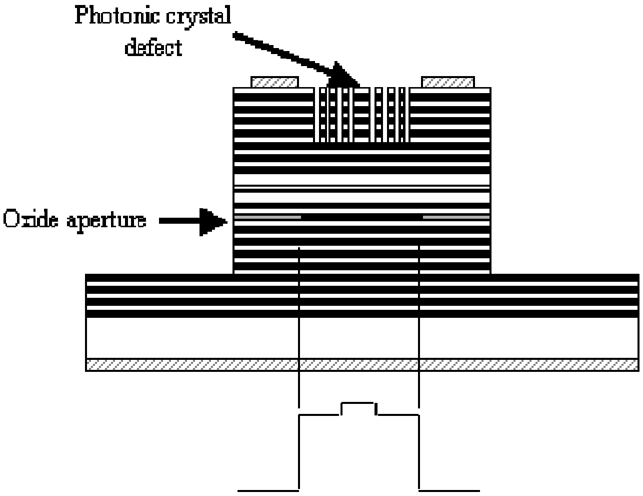

Figure 2. Cross-section of photonic crystal VCSEL shows effective index profile. An approximate index profile is indicated. The etched holes introduce a much smaller controllable index change than the oxidized layer introduces.

electron beam lithography step). The holes are subsequently etched with inductively coupled plasma etching. Figure 3(a) shows a near field image of a photonic crystal-confined VCSEL with a one-hole defect in operation. Figure 3(b) illustrates the etched holes and typical dimension.

The process of fabricating a single-mode photonic crystal VCSEL is also extendible to other material systems besides the GaAs-AlGaAs system used in 850 nm lasers. Because of the simplicity in etching the holes and the adaptability of the regime to other wavelengths (the single mode condition is wavelength independent), it could be used to achieve single mode operation in future GaN blue VCSELs or lasers operating at communications wavelengths such as 1.3 μm or 1.55 μm. Because there is a large degree of freedom in the design space of the photonic crystal pattern (in terms of hole sizes, lattice spacing, and etching depth) [4], the process is robust and reproducible regardless of the underlying material system.

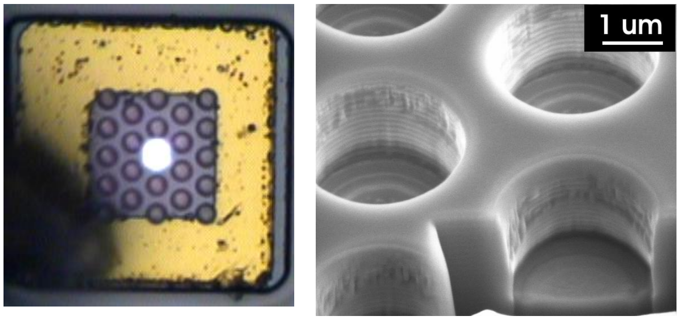

Figure 3. (left) Near field image of photonic crystal VCSEL operating in the fundamental lateral defect mode; (right) Electron micrograph of etched holes. The lower right hole has been milled to show a vertical cross section.

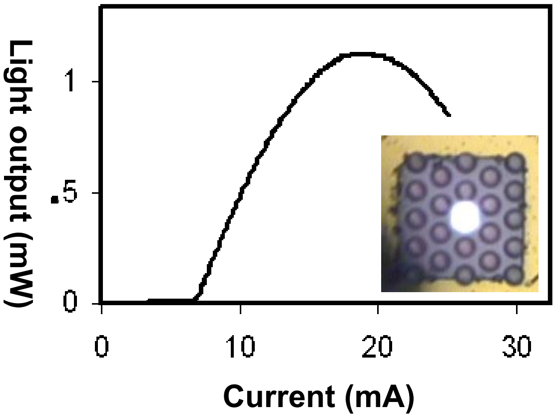

Figure 4. LI curve showing over 1 mW of maximum single mode output power from a photonic crystal VCSEL.

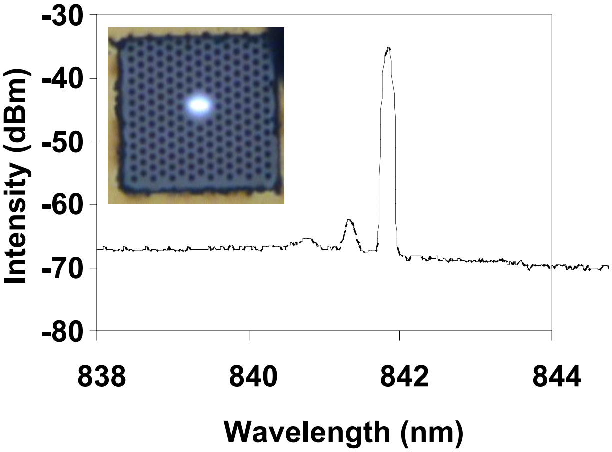

Figure 5. Spectrum from a seven-hole defect photonic crystal laser operating in the fundamental lateral mode.

3. EXPERIMENT

VCSELs containing n-type top DBRs were utilized in order to take advantage of the higher electron mobility (resulting in less electrical resistance in the region of etched holes). Since an oxide aperture was still used to provide electrical confinement, some carriers are lost when passing through the active region in an area laterally outide the central defect area. In spite of the lost current, over 1 mW of single mode output power (with 30 dB side mode suppression) has been achieved in a device containing an oxide aperture, as shown in Figure 4. Figure 5 shows a spectrum from a lasing photonic crystal VCSEL with a seven-hole centralized defect.

Operation with greater output powers and lower threshold currents will also be possible when other forms of current confinement are considered, such as ion implantation which does not introduce any inherent index step laterally into the VCSEL. In addition, the size of the oxide aperture surrounding the central defect in a photonic crystal VCSEL could be optimized such that fundamental mode operation is sustained despite the encroaching low index region caused by the oxidized layer. In the devices shown in Figures 4 and 5, the oxide aperture is placed at least one photonic crystal lattice period outside the central defect. Since no effects on single mode performance were noted, it is clear that the oxide aperture could be smaller without adversely affecting single mode operation while at the same time lowering the threshold current and increasing maximum output power. The addition of the etched holes also introduces an index step that is highly controllable. Introducing an even smaller index step (by using smaller diameter holes, for example), can lead to a wider possible central defect diameter while retaining single mode operation. Coherent coupling between adjacent defects in the photonic crystal lattice has also been demonstrated [8]. Figure 6 shows far field and near field images of a 2-by-2 coupled defect array within a large gain area.

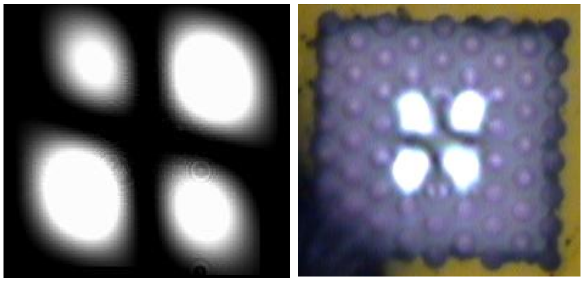

Figure 6. Photonic crystal VCSEL with coupled defects. (a) Far field image illustrating out-of-phase coherent coupling; (b) near field image.

4. SUMMARY

In summary, motivated by the desire to achieve high power single mode operation in VCSELs while at the same time retaining a simplified fabrication process, we introduce the photonic crystal method of confinement as a reliable and robust technique to eliminate higher order transverse modes in VCSELs. Photonic crystal VCSELs have been demonstrated to produce over 1 mW of single mode output power with over 30 dB side mode suppression, and adjacent defects within the photonic crystal lattice have been demonstrated to couple coherently. The photonic crystal confinement process is reproducible because of the inherent freedom in the design space, and employs a simple reliable fabrication process that is extendable to other materials systems such as GaN-based materials or devices operating at communications wavelengths.

5. ACKNOWLEDGEMENTS

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