Single mode photonic crystal vertical cavity lasers

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We report the accuracy of the photonic crystal model in describing the characteristics of vertical cavity surface-emitting lasers with lateral optical confinement consisting of a periodic array of etched circular holes. Experiments were carried out to compare predictions of the photonic crystal model to observed modal device characteristics, and the oxide aperture size was optimized to give maximum output power and lower threshold. The role of loss in improving modal properties was also investigated. Optimized lasers exhibit submilliamp threshold current and operate in the fundamental lateral mode for all currents. © *2006 American Institute of Physics*.
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Operation in the fundamental transverse mode in a vertical cavity surface-emitting laser (VCSEL) is critical for high performance optical communication systems, particularly for long wavelength (1.3–1.55 μm) applications, and sensor applications. Because the VCSEL active region nearly always has a transverse dimension that is larger than its longitudinal length, this laser commonly operates in multiple transverse modes. Lateral confinement of the transverse optical cavity by selective oxidation has allowed control of modal characteristics of small-aperture VCSELs. Selectively oxidized VCSELs have also shown good scalability of threshold current with aperture size down to $\sim$3 μm diameter.[1–3] One drawback, however, of the use of oxide apertures in VCSELs to achieve operation in the fundamental lateral mode is that the oxidation process must be tightly controlled; this control is strongly dependent on the particulars of the epitaxial structure. In addition, high power operation in the fundamental mode is difficult to reproducibly achieve, since the reduction in cavity size limits the power output. Other methods of achieving single mode operation in a VCSEL include surface relief etching where preferential loss to higher-order modes is introduced,[4] or phase-matching modifications to yield reduced mirror loss for the fundamental mode.[5] These methods can achieve high powers, but typically the surface etching depth target cannot deviate strongly from the design requirements. External cavity methods (which are not monolithic),[6] and hybrid oxide/implant designs[7] can also be employed to create single mode VCSELs.

The photonic crystal VCSEL[8–10] allows lithographic control over the modal properties of a device. A cross section of this device is shown in Fig. 1. Air holes, defined through optical or electron beam lithography, are etched into the top distributed Bragg reflector (DBR) of a VCSEL to provide lateral optical confinement around a central defect, formed from single or multiple missing holes. Electrical confinement is provided by an oxide aperture, which can also affect modal operation by encroachment into the central defect region surrounded by the etched holes. The photonic crystal model serves as a simple tool to predict whether a given design (hole diameter, lattice constant, and etch depth) will yield a single mode VCSEL. This model employs a two-dimensional photonic crystal model and a matrix transfer approach to handle the finite etching depth.[9] In previous studies, the model accurately predicted the cavity resonance shifts caused by a broad area of etched holes in a VCSEL wafer,[11] and it could be used to predict modal properties for photonic crystal VCSELs with small defect regions within much larger oxide apertures.[10] The presence of an encroaching oxide aperture and the optical loss introduced by the etched holes, however, also affect the modal properties and are not taken into account in the photonic crystal VCSEL model. While the use of more sophisticated three-dimensional models could provide information into the exact nature of the modal properties, a simple model is preferred to allow straightforward design of single mode VCSELs. The purpose of the present study is to evaluate the photonic crystal model in cases with encroaching oxide apertures to determine its utility. In addition, we parametrically study the effects of loss for the etched holes on the performance of the VCSELs.

The photonic crystal model used in the analysis is similar to that used to analyze photonic crystal fibers,[12] where the holes surrounding a central core region are approximated as a wavelength-dependent effective index calculated from a band diagram. The V parameter is used to evaluate the laser

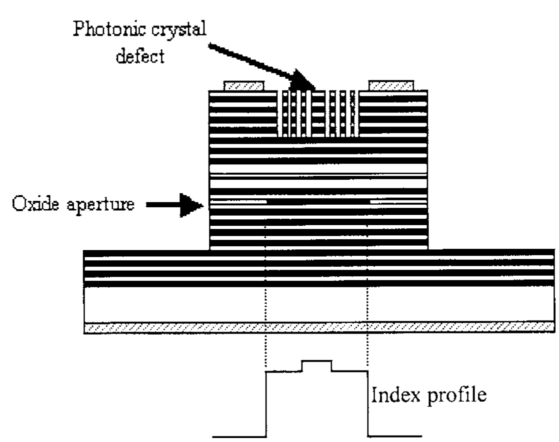

FIG. 1. Cross section diagram of a photonic crystal VCSEL, illustrating the index profile.

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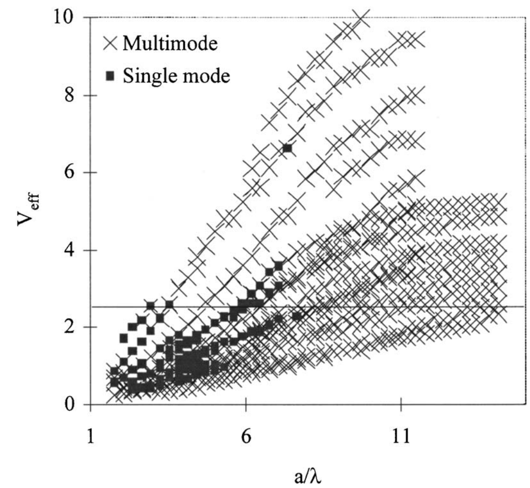

FIG. 2. Comparison of calculated and observed modal properties of photonic crystal VCSELs with lattice constant *a*. Devices are positioned onto the plot with the theoretical model and the actual operation is depicted by the data points.

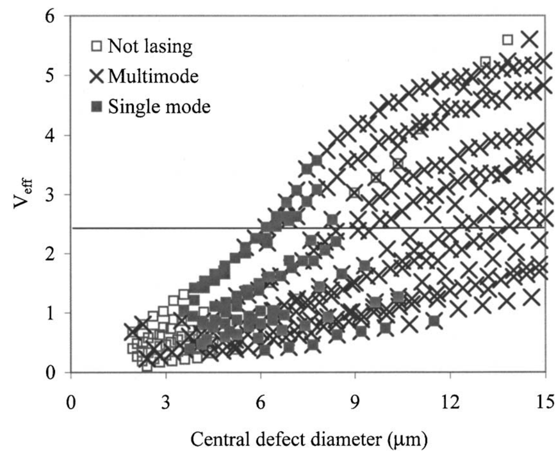

FIG. 3. Comparison of calculated and observed modal properties of photonic crystal VCSELs vs defect diameter.

modal properties.[13] If V_{eff} is greater than 2.4, then a device is predicted to support multiple lateral modes, and if it is less than 2.4 it should only possess a single fundamental mode. The details of the calculation of the effective V parameter in photonic crystal VCSELs are available elsewhere.[9]

A parametric study was designed such that the defect diameter, defined as the separation between the inner holes defining the lasing region, and the oxide aperture width are both varied. Lasers of ten different oxide aperture sizes were fabricated, and for each aperture size the design of the photonic crystal lattice (and thus defect diameter) was varied over a wide range, from encroachment of the oxide aperture into the central lasing region to a separation distance of several periods between the oxide width and defect diameter. The study involved 1652 photonic crystal VCSELs in total, each with a unique design. The experimental results can be used to give empirical constraints to be added to the photonic crystal model so that it can retain its utility in the presence of an encroaching oxide aperture.

The VCSELs contained 22 and 34 periods in the top and bottom DBRs, respectively, with an epitaxial structure designed for operation at a wavelength of 850 nm. Square mesas were defined for lateral oxidation and square oxide apertures with side lengths ranging from 5 to 27 μm were produced. After the selectively oxidized VCSEL fabrication was complete, a layer of silicon dioxide was deposited to serve as an etch mask for defining the holes. Electron beam lithography was used with a positive resist to define the holes, and then subsequent anisotropic etches through the silicon dioxide layer into the mesas created the holes. The etching depth varies with hole diameter, but is not critical for achieving single mode operation. The varying hole depth is accounted for in the calculation of the V_{eff} parameter, which increases with increasing etch depth.[9]

The results of the accuracy of the modal predictions for all lasers studied are shown in Figs. 2 and 3. For the purposes of this study, single mode operation is defined as greater than 30 dB ratio between the fundamental mode and higher order transverse modes at the point of maximum output power. As expected, for most lasers with $V_{eff}<2.4$, we observe in Fig. 2 single mode operation. However, for low values of V_{eff} (usually corresponding to very shallow etches) multiple transverse modes confined by the oxide aperture are found as in previous studies.[10] These are believed to be caused by insufficient loss from the etched holes, resulting in photonic crystal radiation modes extending beyond the central defect, lasing with confinement from the oxide aperture. The theoretical prediction of "endlessly single mode" operation with increasing lattice constant, a, breaks down for large values, specifically when a/λ is greater than ~7. This is due to other contributions to refractive index besides the etched holes, such as thermal lensing or electronic effects. Figure 3 shows the modal operation as the central lasing defect size varies, and includes devices that did not laser. Again, single mode is expected and observed for devices with $V_{eff}<2.4$ and cavity diameter greater than 4 μm. Some multimode devices lie within the area of predicted single mode operation (and vice versa). For these devices, the majority are caused by an encroached oxide aperture (leading to greater index confinement), while in the other cases, the lasers operated primarily single mode but did not achieve 30 dB side mode suppression. Devices in Fig. 3 with small defect apertures are unable to lase because of the high loss associated with increased size of etched holes or increased numbers of etched holes within a fixed oxide aperture.

The effect of the oxide aperture is illustrated in Fig. 4. A

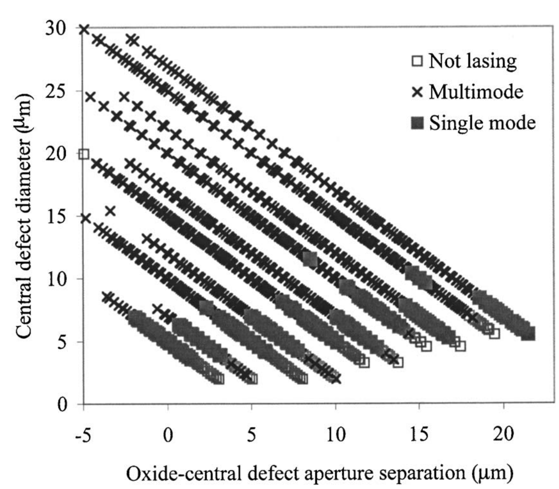

FIG. 4. Observed modal properties of photonic crystal VCSELs vs defect diameter and the width difference between the oxide aperture and the defect diameter.

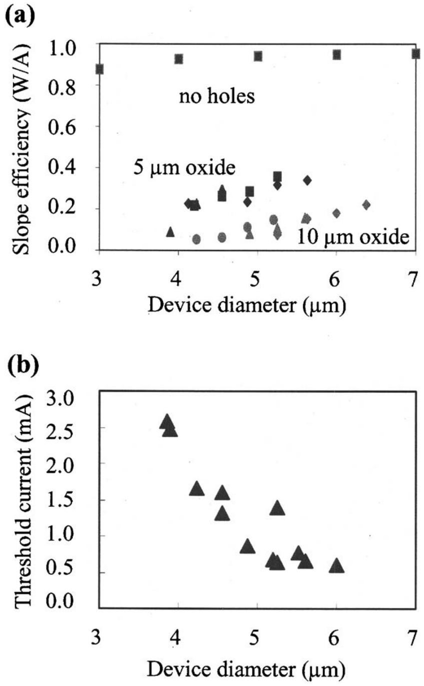

FIG. 5. Effects of optical loss on operation of photonic crystal VCSELs. (a) Slope efficiency for oxide VCSELs and photonic crystal VCSELs with two different oxide aperture widths. The device diameter represents the oxide width for the oxide VCSELs or the defect lasing region in the photonic crystal VCSELs; (b) threshold currents of photonic crystal VCSELs vs defect diameter for devices with a fixed oxide aperture of 7 μm.

clear progression can be seen for all ten oxide aperture sizes, starting with not lasing, to lasing in the fundamental mode, and finally to lasing in multiple modes as the defect diameter increases relative to the oxide aperture size. The most promising devices are those with central defect diameters of 4–7 μm with 5–10 μm oxide apertures. For the devices with defect diameters of 7 μm, the 5 μm oxide aperture widths still yielded operation in the fundamental mode. Because the oxide apertures of these devices actually penetrate into the central lasing region defined by the photonic crystal, the etched holes likely introduce considerable optical scattering loss to the higher order modes supported by the oxide aperture to prevent them from lasing. Scattering loss has also been predicted in studies where three-dimensional models have been employed[14] and verified through mode size measurements.[15]

Figure 5 illustrates how threshold current and slope efficiency scale with the central defect diameter for a given oxide aperture. Figure 5(a) shows that slope efficiency is reduced with the presence of the etched holes. Three data sets are shown, allowing comparison of oxide VCSELs without holes (not necessarily single mode), and single mode photonic crystal VCSELs with two fixed oxide aperture sizes (5 and 10 μm). Single mode operation is accompanied by a reduction in laser efficiency. The slope efficiency increases with photonic crystal aperture because of reduced excess loss from the etched holes and better current injection uniformity as the device diameter approaches the size of the oxide aperture.

Figure 5(b) illustrates that with a fixed oxide aperture of 7 μm, increasing the size of the central defect defined by the etched holes reduces the threshold current. Because all the devices of Fig. 5(b) have the same oxide aperture width, the increase in threshold current is due to optical scattering loss caused by increasing numbers of holes present within the oxide aperture. Optical loss from the etched holes is beneficial in allowing the oxide aperture to encroach upon the central lasing region without significantly affecting modal characteristics, but it also lowers the slope efficiency. Nevertheless, greater single mode power with submilliamp threshold can be obtained with this method than from selectively oxidized devices without modifications. The maximum output power of the VCSEL with the lowest threshold current in Fig. 5(b) is over 1.5 mW, and greater than a milliwatt was obtained for over half of all single mode devices in this study. Over 3 mW has been obtained in optimized photonic crystal VCSELs.[16]

In summary, we have shown that the photonic crystal model can be reliably used to predict modal operation of photonic crystal VCSELs, even in cases of oxide aperture encroachment if empirical constraints are considered. For device designs with $0.6 < V_{\mathrm{eff}} < 2.4$ and an oxide aperture greater in diameter than the central defect region, single mode operation can be reproducibly achieved. To produce high single mode power in 850 nm VCSELs, 10 μm is an upper limit on central defect region diameter. The use of photonic crystal holes to achieve single mode operation has been shown to yield devices with submilliamp threshold current and over a milliwatt of output power.

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