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Progress in Photonic Crystal Vertical Cavity Lasers

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SUMMARY Recent progress and achievements in creating single fundamental mode vertical cavity lasers with the technique of etching a 2-dimensional pattern of photonic crystal holes into the top distributed Bragg reflector are described. A simulation method for the design of single mode lasers is described, along with accuracy and limitations in predicting modal properties in these devices. Progress in improving output power, methods of lowering threshold currents, and small signal modulation of single mode lasers are discussed.
key words: *VCSEL, photonic crystal, single mode laser*

1. Introduction

The operation of a laser in a stable single fundamental mode is important for a variety of applications, such as short and mid-range optical high quality local area networks and storage area networks. For these purposes, vertical cavity surface-emitting lasers (VCSELs) show promise over distributed feedback lasers for a variety of reasons: easy array scaling, low power consumption, convenient on-wafer characterization, easy packaging, and high volume and low-cost manufacturability.

Previous methods for producing high power fundamental [1]–[3] and higher order [4] single mode operation in a VCSEL have been reported. Among those methods investigated for improving single mode power characteristics are surface relief etching [3] and external cavity methods (not monolithic) [5], where preferential loss to higher-order modes is introduced, and hybrid oxide/implant designs [2]. The photonic crystal (PhC) VCSEL involves the use of a pattern of etched holes in the top distributed Bragg reflector (DBR) to achieve lateral confinement [6]–[8]. Some potential advantages with this confinement method are a finely-tunable lateral index step (unavailable with oxide-confined VCSELs) which is wavelength dependent, leading to the ability to enlarge the optical emission area while still maintaining operation in the fundamental mode with only weak dependence on etching depth. Thus precise etching depths are not needed, allowing for reproducibility. Disadvantages of etching photonic crystal holes include increased resistance and optical losses leading to higher threshold currents and voltage than in an otherwise identical but unetched (albeit multimode) VCSEL.

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Photonic crystal (PhC) vertical cavity surface-emitting lasers (VCSELs) have demonstrated reproducible operation in a single fundamental transverse optical mode [6]–[8]. Unlike in-plane two dimensional photonic crystal structures where the defect mode often lies within a frequency bandgap, the type of defect mode created in the VCSEL described here is a guided out-of-plane mode confined in a way similar to the case of a solid-core photonic crystal fiber [9]. With the proper selection of hole depths, diameters, and arrangement, this index confinement can be exploited to create single mode photonic crystal defect VCSELs that have the potential for low threshold currents and high output powers [8]. First a theoretical treatment based on photonic crystal frequency-domain analysis will be described. Next, we discuss the fabrication and characterization of PhC-VCSELs. Finally we summarize and comment on future research.

2. Theory

A PhC-VCSEL consists of a conventional oxide-confined or ion-implanted VCSEL with holes etched into the top DBR in the pattern of a photonic crystal. Lasing occurs through a centralized defect that is sufficiently isolated laterally from the index step of the oxide (or thermal lens of an implant). Figure 1 illustrates a cross sectional diagram of such a device. The light propagation is parallel to the refractive index variation of the photonic crystal.

The effects of the etched holes on the lasing can be

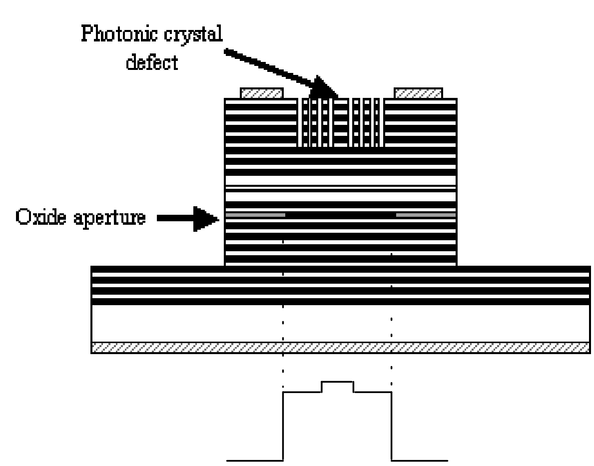


Fig. 1 Cross sectional diagram of a PhC-VCSEL indicating an equivalent index step profile beneath the diagram.

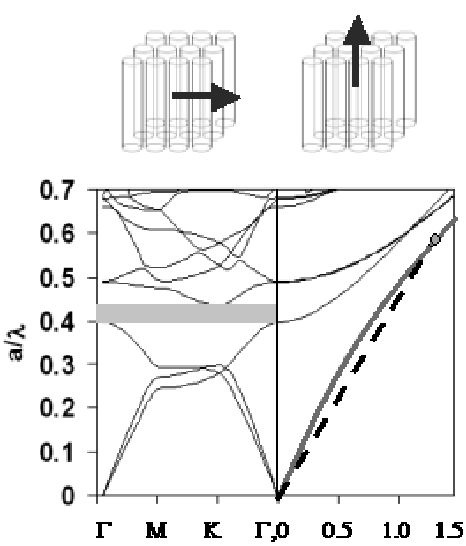


Fig. 2 Band diagram of hexagonal array photonic crystal consisting of infinite holes in GaAs. The vertical axis represents emission frequencies. The left hand horizontal axis corresponds to directions perpendicular to the lattice holes, while the right hand horizontal axis is the out-of-plane wave vector (parallel to the lattice). A straight-line used to determine the effective index of the lowest out-of-plane propagation vector is illustrated, and the in-plane gap is shaded.

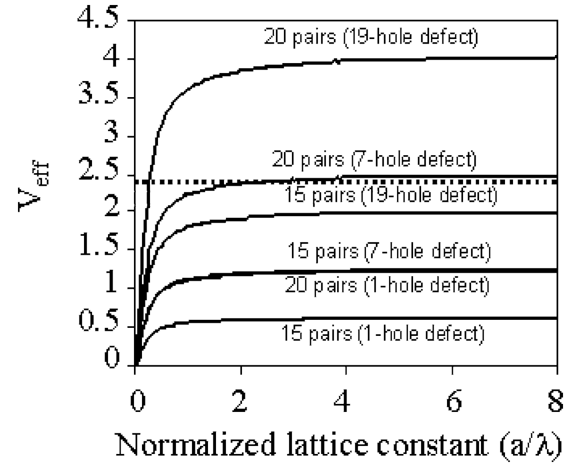


Fig. 3 Theoretical modal properties for two different etch depths and three different central defect diameters for the case where the hole diameter is half the lattice constant. Etch depth is measured in periods, or pairs, of the top DBR. The single mode cutoff condition is indicated by the dotted line.

analyzed theoretically by first considering the case of a perfect photonic crystal in bulk GaAs. The effective index n of the material containing the photonic crystals can be found by taking the slope of the propagation vector length to the propagation constant, k_z/k_0, of the straight line of the lowest order allowed out-of-plane mode as shown in the band diagram in Fig. 2. This operating point is fixed by the lattice constant and wavelength. Extracting the index in this way causes it to be wavelength dependent: as the wavelength changes, the slope of the straight line changes. This is essentially the same method used to determine the lateral effective index in the case of an "endlessly single mode" photonic crystal fiber [9]. Ultimately, the propagating modal characteristics of the VCSEL are determined principally by the design parameters of the photonic crystal lattice. These parameters include the hole diameter, lattice constant, number of holes missing from the defect region, and etching depth. The interaction of the parameters determining single fundamental mode operation is quantified by use of the V_{eff} parameter [7], or normalized frequency, which is given by

$$V_{eff} = \frac{2\pi r}{\lambda} \sqrt{n_m^2 - n_{eq}^2} \tag{1}$$

where n_{eq} is the equivalent refractive index of the photonic crystal region surrounding the central defect (determined from band diagram analysis as just described and etching depth dependence which will be discussed), n_m is the unmodified index of the defect region, and r is the radius of the same defect region. The radius of that region depends on the lattice constant and the number of holes missing; it is approximated to be the distance from the defect center to the edge of the nearest adjacent hole. λ is the free-space wavelength. If V_{eff} is less than 2.405, the structure is considered to be single mode as in standard fiber mode theory [9].

In an actual VCSEL, each DBR layer penetrated by etched holes should be treated separately to account for the finite etch depth of the etched holes. Because the difference in index between adjacent DBR layers is relatively small, a homogeneous background material that is penetrated by the photonic crystal can be used to determine the expected index change for each DBR layer that is penetrated by the holes with the band diagram analysis described above. This introduces an error, especially at the top of the DBR where the adjacent layer is air, but it is assumed that because the strength of the optical field is low at that point the contribution of that error is not significant. Absorption and scattering loss is also not included in this analysis, which causes inaccurate results as the lasing aperture size increases. As will be shown, combining the photonic crystal model described with empirical data can yield an accurate design space, avoiding a fully three-dimensional model.

At this point in the analysis, DBR layers in the area surrounding the central lasing region that are penetrated by photonic crystal holes are replaced by uniform layers with the appropriate calculated indices. Since cavity resonance wavelength shifts correspond to changes in effective index [10], a transmission matrix approach can be used to determine the effective index step between the DBR with photonic crystals of finite etch depth and the central unetched region by considering the resonance wavelength difference between the two regions. A lateral index step calculated in this way is typically 10^{-3}, much smaller in magnitude than what would be expected if simply considering the air filling factor introduced by the holes. After all equivalent indices are known for a given structure, the V_{eff} parameter calculated by Equation (1) indicates if the device will operate in a fundamental lateral mode. For a typical 850 nm VCSEL epitaxial structure, Fig. 3 illustrates the modal properties for different central defect sizes. Similar to the way in which a photonic crystal fiber can remain single mode over a wide range of wavelengths, the PhC-VCSEL is expected to remain single mode over a wide range of lattice constants and hence defect sizes. Thus for large lattice constants high power single mode operation could occur.

3. Experiment

3.1 Verification of Model

The first experimental verification of the model came from directly measuring the resonant frequency shifts from etched holes in VCSEL epitaxial material. The wavelength difference before and after the holes were etched into the top DBR corresponded with that predicted by the photonic crystal model used here with reasonable accuracy [11]. Following this, processes for fabricating PhC-VCSELs were developed.

A focused ion beam of gallium ions can be used with a prefabricated oxide-confined VCSEL where a silicon dioxide protective layer had first been deposited and then subsequently removed after the mill. Another method of fabrication is to first deposit silicon dioxide, and then pattern it with use of electron beam or optical lithography and a suitable resist. In each case, VCSELs can be characterized prior to the addition of the etched photonic crystal holes.

The photonic crystal structure fabricated to test the model contains a triangular array of circular air holes of varying lattice constant surrounding a central lasing region where one, seven, or nineteen air holes are absent. Experimentally we find single mode operation is achieved through a combination of the index guiding described above and loss that prevents the lasing of allowed photonic crystal modes extending to the oxide aperture. One exception occurs for holes etched too shallow; there is insufficient index contrast and loss to confine the light within the central region and the index confinement from the oxide aperture is able to produce a higher order lasing mode [8]. Also, with deeper holes where multimode operation would normally be expected, single mode operation can occur because of additional loss [12].

The photonic crystal model predicts the equivalent index changes with sufficient accuracy to predict whether a given device will operate in a single lateral mode [8]. This is illustrated in Fig. 4 for several hundred devices of different designs all fabricated on the same epitaxial structure. In this test, it was discovered that there is a lower empirical boundary (~0.6) on values of V_{eff} as well as the upper theoretical boundary of 2.4. The lower V_{eff} values correspond to the case where loss is insufficient to prevent the extended photonic crystal oxide-confined modes from lasing. In Fig. 4, it is also apparent that the photonic crystal model is also not applicable to cases with large apertures, likely due to thermal instability. A thermally-induced effective index change could overwhelm a smaller index change introduced by the etched holes. In addition, Fig. 4 incorporates some devices

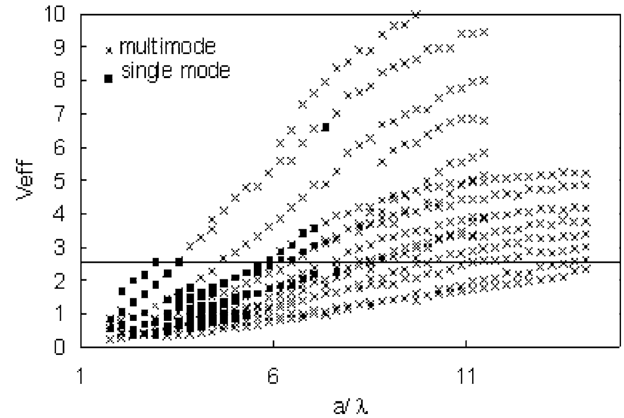


Fig. 4 Experimental results of modal properties of fabricated photonic crystal VCSELs. The dotted line between multimode and single mode operation indicates the theoretical boundary. Each data point represents the type of operation experimentally observed.

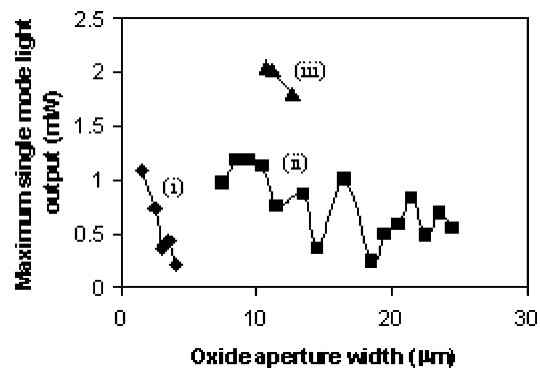


Fig. 5 Maximum single mode output power dependence on oxide aperture diameter for (i) oxide VCSELs, (ii) PhC-VCSELs with 6.7-μm optical aperture diameter and (iii) PhC-VCSELs with 8-μm optical aperture diameter.

where the oxide aperture encroached too closely to the central lasing region of the device—these devices with small apertures were experimentally multimode lasers yet had a single-mode design. How closely the oxide aperture can encroach upon the photonic crystal defect region is discussed in the next section.

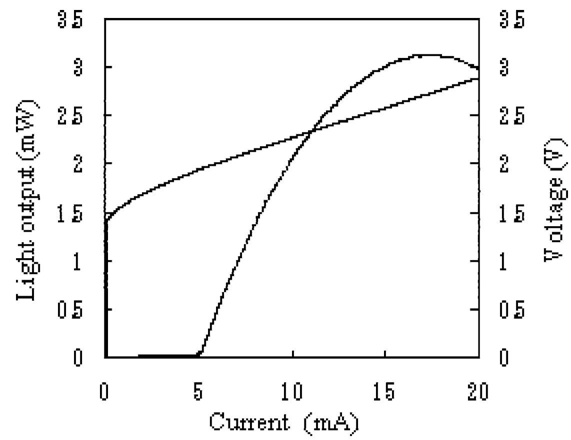
3.2 Improving the Output Power

In the devices just presented, oxide aperture widths were usually much larger than the defect diameters to prevent the large index step introduced by the oxide aperture from dominating the smaller index of the photonic crystal confinement. Greater output power, however, can be achieved with oxide apertures closer in size to the optical diameter [13]. Photonic crystal patterns of two different optical aperture diameters were etched into VCSELs of varying oxide aperture widths. The measured maximum single mode output power, defined as > 30 dB side mode suppression ratio, is shown in Fig. 5. Figure 5 illustrates that as the oxide aperture width is decreased, maximum output power is increased, with a concurrent trend of decreasing threshold currents. When the electrical aperture (defined by the oxide aperture) is nearly equal to the optical aperture (defined by the photonic crystal defect) there is minimum current wasted to spontaneous emission around the periphery of the laser. It is evident from Fig. 5 that the encroaching oxide aperture can approach the central lasing region without adversely affecting modal characteristics.

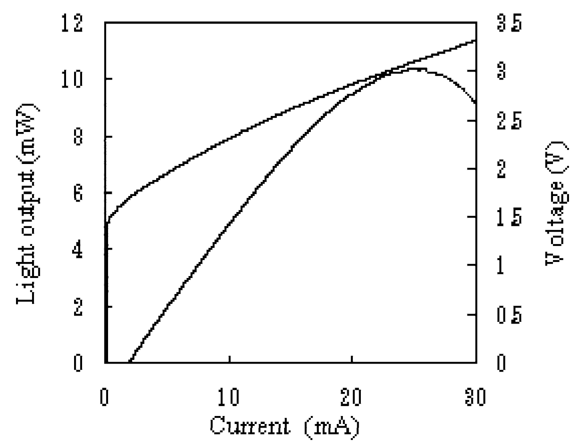
Using the results of Fig. 5, high single mode output power VCSELs have been fabricated. The oxide aperture that we chose is 9 μm in width and the photonic crystal aperture is 6.6 μm in diameter. This device was fabricated from a wafer designed for increased power conversion efficiency (lower refractive index contrast in the DBR mirrors to reduce the mirror reflectivity). The lattice constant is 4.4 μm; the hole diameter is 2.2 μm; and the target depth is 16 mirror pairs of the top DBR. This corresponds to a conservative design of Fig. 5(ii) to ensure single mode operation, but higher output power is possible from a design like that of Fig. 5(iii), albeit with more stringent fabrication requirements [14].

Figure 6(a) shows the light output from an improved device that emits 3.1 mW of output power in the fundamental mode with over 30 dB side mode suppression. Figure 6(b) shows the light output of the oxide-confined VCSEL without the etched holes. The conventional oxide-confined VCSEL in Fig. 6(b) operates in multiple transverse modes from threshold. Figure 7 shows the spectrum of the PhC-VCSEL at rollover illustrating the single mode characteristic. Comparison of Figs. 6(a) and 6(b) shows that an increase of threshold current and reduction in total output power occurs with the addition of the etched holes, although greater fundamental output results. Assuming a circular photonic crystal defect lasing aperture that extends to the inner edges of the holes surrounding the central area, approximately 34 μm^2 area is useful for lasing, compared to a gain area of approximately 80 μm^2. Thus, nearly 60% of the carriers are wasted so some decrease in light output is expected at the same level of current injection. The decrease of the slope efficiency and the increase in threshold current is also likely due to the increased scattering loss introduced by the etched holes compared to the same device without holes and equivalent oxide aperture size.

The reason the oxide aperture can encroach into the periodic structure without affecting the photonic crystal-induced mode properties is likely due to the strong lateral confinement in the top mirror region from the etched holes, the vertically-distributed index contrast, and loss from the etched holes eliminating extended photonic crystal modes that are confined by the oxide aperture and would otherwise lase. Because focused ion beam milling was employed in creating the holes, depth could be easily controlled in the study. The effect of varying etching depth on threshold current and rollover current was examined and it was found that within the range of expected single mode operation predicted from the photonic crystal model there were no significant trends regarding the single mode property. Etching within 10 pairs of the target (5 pairs shallow or



(a)



(b)

Fig. 6 (a) Optimized PhC-VCSEL with 9-μm oxide aperture operating in a single fundamental lateral mode with over 3.1 mW output power. (b) Selectively-oxidized VCSEL with 9-μm oxide aperture and no etched holes operating in multiple lateral modes.

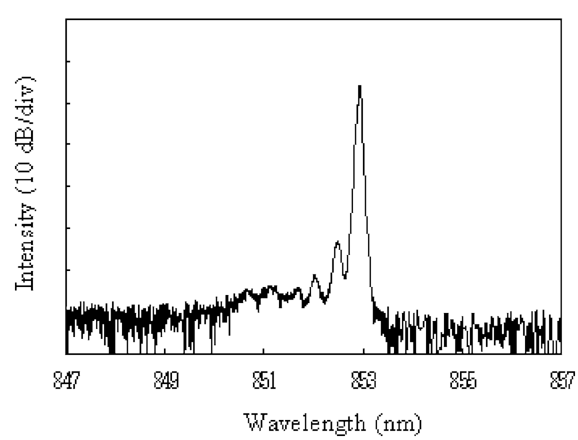


Fig. 7 Spectral characteristic of the optimized single mode PhC-VCSEL (corresponding to Fig. 6(a)) at maximum output power. Over 30 dB side mode suppression is maintained through rollover.

deep) resulted in single mode operation with at least 30 dB of side mode suppression in this case. The hole sizes involved would allow the use of optical lithography, and the

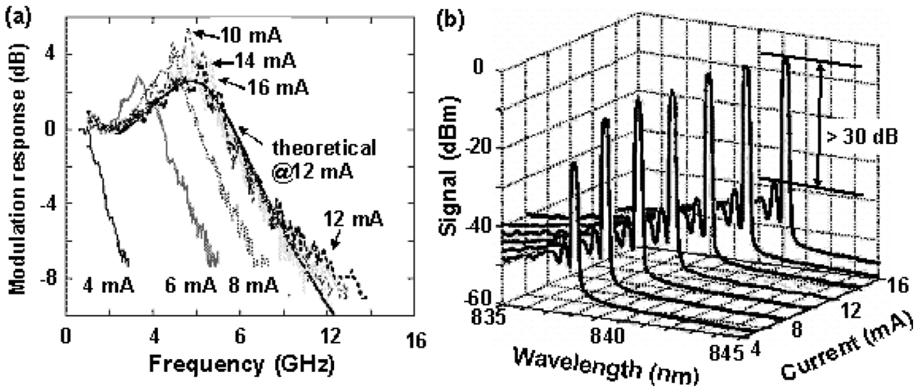


Fig. 8 (a) Small signal modulation and (b) Emission spectrum at the 3-dB frequency at each current of a PhC-VCSEL.

etch depth is not critical in achieving reasonable amounts of single mode power.

3.3 High Speed Characterization

The high speed modulation characteristics were investigated to determine if the PhC-VCSEL is appropriate as a single mode source for communications purposes [15]. In this case, an oxide confined VCSEL with coplanar contacts was fabricated before incorporation of the photonic crystal holes. The mesa was etched down 10 periods into the bottom distributed Bragg reflector (DBR) using inductively coupled plasma (ICP) etching after deposition of the top p-contact. The n-contact was deposited on the bottom of the mesa. A coplanar cascade contact with 125 μm pitch for high speed modulation was deposited on a planarized surface made of polyimide.

After the oxide VCSEL fabrication, a triangular photonic crystal lattice pattern with a single defect was etched into the top DBR of the oxide-confined VCSEL with a $10 \times 10\,\mu\mathrm{m}^2$ wide oxide aperture. The circular holes were lithographically defined using focused ion beam etching into a SiO_2 mask. The hole diameter-to-lattice constant ratio was 0.5 with a single hole missing to form the lasing region, and the depth of the etched holes was measured to be approximately 15 periods of the top DBR, which contains 27 periods total.

Characterization of the VCSELs before and after the addition of photonic crystal pattern was carried out at room temperature. The small signal modulation bandwidth and emission spectra under dc and small signal modulation were measured. The small signal bandwidth of the single fundamental mode from the PhC-VCSEL is shown in Fig. 8(a) with a maximum 3 dB rolloff frequency of 9 GHz. With increasing injection current, the 3 dB bandwidth increases linearly up to 12 mA before saturation. The solid line in Fig. 8(a) is a fit to the experimental data at 12 mA injection current using a three-pole approximation of the modulation response equation [16]. The 3 dB bandwidth of the multimode $10 \times 10\,\mu\mathrm{m}^2$ oxide aperture VCSEL without etched holes is more than 11.5 GHz. Emission spectra of the PC-VCSEL under small signal modulation is shown in Fig. 8(b). The single fundamental mode property with more than 30 dB SMSR is retained unlike an earlier reported result [17], although the SMSR is decreased by 10 dB compared to CW operation. Figure 9 shows a filtered eye diagram obtained at 2.5 Gbps under large signal modulation.

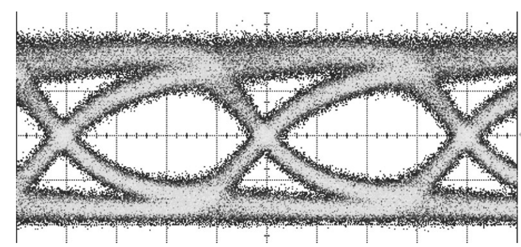


Fig. 9 Filtered eye pattern at 2.5 Gbps.

The modulation bandwidth of conventional oxide-confined VCSELs is strongly influenced by the oxide aperture size, where lasers with smaller oxide apertures produce higher modulation bandwidth [18]. Note that the device in Fig. 8 has a relatively large oxide aperture, but maintains a small size fundamental mode. This may prove advantageous for communication applications where single mode operation and high device reliability are required.

4. Conclusion

In summary, it is shown that a photonic crystal frequency-domain model can provide a design scheme to fabricate on-demand single-fundamental-mode VCSELs with a wide tolerance in fabrication parameters to maintain this important property. It is shown that the oxide aperture can encroach on the optical aperture of a PhC-VCSEL without significantly altering the modal characteristics, and single mode powers of at least 3.1 mW can be achieved. Small signal bandwidths of up to 9 GHz have been reported. Etching depth requirements for single fundamental mode operation are not stringent, important for reproducibility in fabrication.

The use of photonic crystal patterns enables other possible uses in a VCSEL. For example, coherent coupling between two adjacent cavities has been reported [19]. Moreover the use of photonic crystals to achieve smaller diameter optical mode sizes may be possible [20]. Finally, recent experiments where a single ring of holes of triangular shape were considered [21] indicate that even greater single mode powers may be achievable with essentially the same fabrication procedure. Therefore the combination of patterned holes introduced into the top facet of the VCSEL may be important for future applications.

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