# Single fundamental mode photonic crystal vertical cavity laser with improved output power

A.J. Danner, T.S. Kim and K.D. Choquette

The single fundamental mode output power of photonic crystal vertical cavity lasers is improved by varying sizes of oxide apertures and defect lasing apertures. A maximum output power of 3.1 mW in the fundamental mode has been achieved with a new fabrication process that involves only focused ion beam etching to create holes in selectively oxidised VCSELs.

*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 networks (high quality local area networks and storage area networks). For these purposes, vertical cavity surface-emitting lasers (VCSELs) show more promise in many cases over distributed feedback (DFB) lasers for a variety of reasons: easy array scaling, low power consumption, convenient on-wafer characterisation, easy packaging, and high volume and low-cost commercial manufacturability.

Photonic crystal vertical cavity lasers (PhC-VCSELs) have been shown to give reproducible operation in a single fundamental transverse optical mode [1–3]. This method for creating a singlemode VCSEL shows potential improvements over other methods because of its ease in design and reproducibility in fabrication. 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 in a solid-core photonic crystal fibre. With the proper selection of hole depths, diameters, and arrangement, this index confinement can be exploited to create singlemode photonic crystal defect VCSELs that have the potential for low threshold currents and high output powers [3, 4]. Other methods not making use of etched holes have also been reported producing high power fundamental [5–7] and higher-order [8] singlemode operation.

Owing to the large electrical apertures that have been used previously, only low powers have been achieved in the past because of wasted current passing through an electrical aperture (created from an oxide aperture) but not through the photonic crystal optical aperture. Achieving over 3.1 mW of fundamental singlemode power is reported by allowing an oxide aperture to encroach closer to the photonic crystal lasing aperture. For the first time only focused ion beam milling was used to define the holes.

*Experiment:* The photonic crystal structure examined contains a triangular array of circular air holes of varying lattice constant surrounding a central lasing region where a single air hole is absent. Singlemode operation is achieved in the altered device through a combination of index guiding and mode-selective loss. For holes etched too shallow, there is insufficient index contrast and loss to confine the light within the central region and the oxide aperture is able to produce a higher-order lasing mode [3]. For deeper holes not penetrating the active region, the index guiding is sufficient to eliminate all modes but the fundamental and achieve adequate confinement within the central defect region.

The photonic crystal model predicts the equivalent index changes with sufficient accuracy to predict whether a given device will operate as in a single lateral mode [2] (an average index method cannot be used since the hole dimensions are too large). Within this regime of allowed singlemode operation, we have examined the dependence of the oxide aperture size on output power. Photonic crystal patterns of two different optical aperture diameters were etched into VCSELs of varying oxide aperture widths. A focused ion beam of gallium ions was used in this case with a prefabricated oxide-confined VCSEL where a silicon dioxide protective layer had first been deposited and then subsequently removed after the mill. The maximum singlemode output power was measured, defined as >30 dB side mode suppression ratio. Fig. 1 illustrates that as the oxide aperture width is decreased, maximum output power is increased. We also note a concurrent trend of decreasing threshold currents. It is evident from Fig. 1 that the encroaching oxide aperture can approach the central lasing region without adversely affecting modal characteristics. Using the results of Fig. 1, high singlemode output power VCSELs have been fabricated.

The oxide aperture that we chose for the new device on a wafer designed for increased power conversion efficiency is 9 μm in width and the photonic crystal aperture is 6.6 μm in diameter. 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. 1(ii) to ensure singlemode operation, but higher output power is possible from a design like that of Fig. 1(iii) with more stringent fabrication requirements.

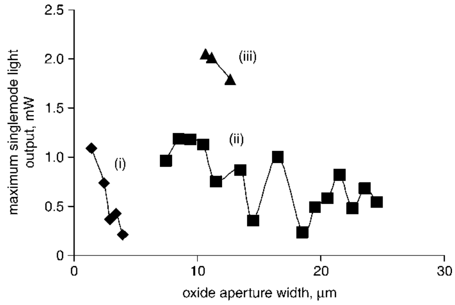


**Fig. 1** *Maximum singlemode output power dependence on oxide aperture diameter*

(i) oxide VCSELs
(ii) PhC-VCSELs with 6.7 μm optical aperture diameter
(iii) PhC-VCSELs with 8 μm optical aperture diameter [9]

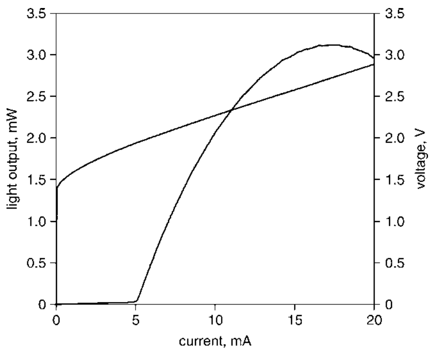


**Fig. 2** *Optimised photonic crystal VCSEL with 9 μm oxide aperture operating in single fundamental lateral mode with over 3.1 mW output power*

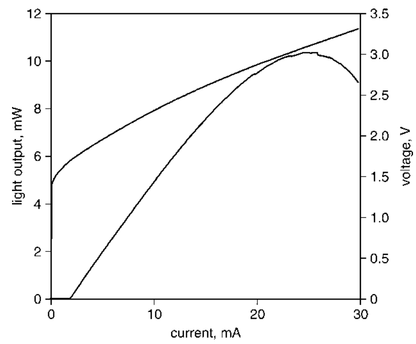


**Fig. 3** *Selectively-oxidised VCSEL with 9 μm oxide aperture and no etched holes operating in multiple lateral modes*

Fig. 2 shows the light output from the improved device that emits 3.1 mW of output power in the fundamental mode with over 30 dB side mode suppression. Fig. 3 shows the light output of the oxide-confined VCSEL without the etched holes. The conventional oxide-confined VCSEL in Fig. 3 operates in multiple transverse modes from threshold. Fig. 4 shows the spectrum of the PhC-VCSEL at rollover illustrating the singlemode characteristic. It is evident that a reduction in maximum output power occurs with the addition of the etched holes. Assuming a circular photonic crystal defect lasing aperture that extends to the inner edges of the holes surrounding the central area, approximately 34 $\mu m^2$ area is useful for lasing, compared to a gain area of approximately 80 $\mu m^2$. Thus, nearly 60% of the carriers are wasted so some decrease in light output is expected at the same level of current injection. The increase in threshold current is likely due to the increased optical loss introduced by the etched holes compared to the same device without holes and equivalent oxide aperture size.

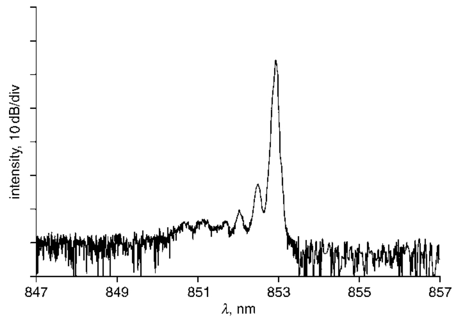


**Fig. 4** *Spectral characteristics of optimised singlemode PhC-VCSEL (corresponding to Fig. 2)*

Over 30 dB side mode suppression is maintained through rollover

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 oxide-confined modes that would otherwise lase. Because focused ion beam milling was employed in creating the holes, depth could be controlled easily 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 singlemode operation predicted from the photonic crystal model there were no significant trends regarding the singlemode property. Etching within 10 pairs of the target (5 pairs shallow or deep) resulted in singlemode 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 etch depth is not critical in achieving reasonable amounts of singlemode power.

*Conclusion:* It is shown that the oxide aperture can encroach on the optical aperture of a PhC-VCSEL without altering significantly the modal characteristics, and singlemode powers of at least 3.1 mW can be achieved. Etching depth requirements for single fundamental mode operation are not stringent, important for reproducibility in fabrication.


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