# Single fundamental mode photonic crystal vertical cavity surface emitting laser with 9 GHz bandwidth

T.S. Kim, A.J. Danner, D.M. Grasso, E.W. Young and K.D. Choquette

A record 9 GHz small signal modulation in a single fundamental mode photonic crystal vertical cavity surface emitting laser is demonstrated for the first time. The device is designed by incorporating etched photonic crystal holes in the top distributed Bragg reflector for optical confinement. Emission spectra measured during small signal modulation confirms single fundamental mode operation.

*Introduction:* Stable single fundamental mode operation of a laser has drawn attention for a variety of applications in short and mid-range high quality optical networks, such as local area networks (LAN) and storage area networks (SAN). For these purposes, vertical cavity surface-emitting lasers (VCSELs) have been considered as promising optical sources over distributed feedback lasers not only because of their easy array scaling, on-wafer characterisation, low power consumption, and easy packaging, but also because of high volume and low cost manufacturability.

Despite these promises, the development of a VCSEL which operates in a single fundamental mode during modulation has been limited due to device parasitics such as large intrinsic resistance and capacitance [1–7]. The 3 dB small signal modulation bandwidth for multimode VCSELs has been reported as high as 14.5 GHz for a proton-implanted VCSEL [2, 3] and 17 GHz for an oxide-confined VCSEL [4]. However, the highest reported singlemode small signal modulation is 6 GHz for an oxide-confined VCSEL [5] and 8.5 GHz for a proton-implanted VCSEL [6]. For oxide-confined VCSELs, constraining the thin oxide apertures to less than 3 μm in diameter which is necessary for single fundamental mode operation, reduces the rollover current and limits the output power, as well as creating a significant challenge for mass production. The decrease in rollover current and high capacitance caused by a thin oxide layer limits the modulation bandwidth of oxide-confined VCSELs [1, 4–6], whereas proton-implanted VCSELs suffer from thermal lensing which limits their modulation bandwidth [2].

It has been shown that singlemode operation of a VCSEL under continuous wave (CW) operation might be changed into multimode operation when the current is modulated. For example, a singlemode VCSEL with a 30 dB side mode suppression ratio (SMSR) exhibited multimode operation with an SMSR of 15 dB under 2.5 Gbit/s large signal modulation [7]. A VCSEL with micromachined surface relief demonstrated consistent singlemode operation both under CW and small signal modulation up to 5 GHz, but it operated in a single higher order transverse mode [8]. Another approach to attain a stable single fundamental mode operation is the incorporation of a photonic crystal pattern in the VCSEL (PC-VCSEL) [9–11], but the modulation behaviour of this device has not been studied. We report a PC-VCSEL which operates in a single fundamental mode with a record 9 GHz small signal bandwidth. Emission spectra under CW and small signal modulation conditions show that the PC-VCSEL remains in single fundamental mode operation.

*Device description:* The oxide-confined VCSEL 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. The oxide aperture was formed by wet oxidation at 430°C. A coplanar cascade contact with 125 μm pitch for high-speed modulation was deposited on a planarised 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 $10 \times 10\ \mu m^2$ wide oxide aperture using ICP etching. The holes were lithographically defined using focused ion beam etching into an $SiO_2$ mask. The lateral index around a single defect can be controlled by the hole diameter-to-lattice constant ratio and etching depth [10]. This ratio was 0.5 in the PC-VCSEL reported here and the depth of the etched holes was measured to be approximately 15 periods of the top DBR, which contains 27 periods total. The PC-VCSEL was fabricated with $10 \times 10\ \mu m^2$ electrical oxide aperture and $35\ \mu m^2$ optical photonic crystal defect apertures.

*Measurements:* Characterisation of the VCSELs before and after the addition of photonic crystal pattern was carried out at room temperature. The small signal modulation bandwidth was measured for all devices using an HP 8510C network analyser. Emission spectra of the PC-VCSEL under CW and small signal modulation were measured using an Agilent 86141B optical spectrum analyser. All of these measurements were performed on-wafer using coplanar cascade contacts.

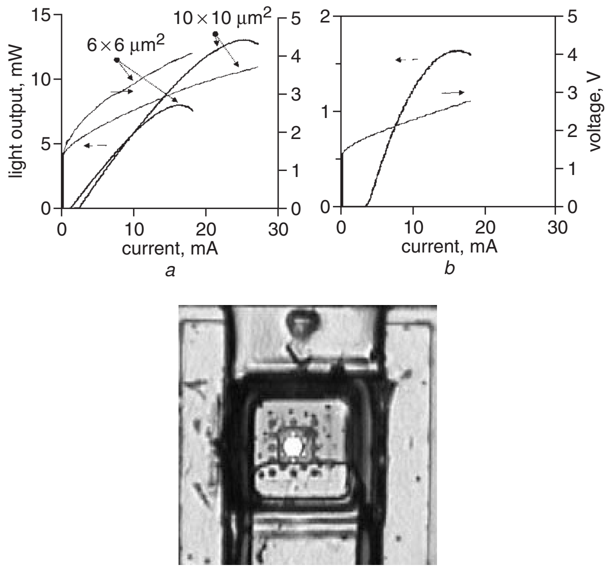


**Fig. 1** *CW characteristics of oxide-confined VCSELs and PC-VCSEL and near field image of PC-VCSEL*

*a* Oxide-confined VCSEL *b* PC-VCSEL *c* Near field image

Fig. 1*a* shows CW characteristics of the oxide-confined VCSELs with aperture size of $6 \times 6\ \mu m^2$ ($36\ \mu m^2$ cross section area) and $10 \times 10\ \mu m^2$ ($100\ \mu m^2$). The CW characteristics and a near field image for the PC-VCSEL with cross section area of $35\ \mu m^2$ are shown in Figs. 1*b* and *c*, respectively. The near field image indicates that lasing is in a smaller central region for the PC-VCSEL compared to the oxide-confined VCSELs. An oxide aperture is present for electrical confinement in the PC-VCSEL, but is sufficiently larger than the central lasing region so as not to interfere with the index shift created by photonic crystal holes. The separate optical and electrical confinement provides better control of single fundamental mode operation than in the oxide VCSELs. The relative large aperture sizes of the oxide confined VCSEL in this experiment cause the lasers to operate multimode. However, the photonic crystal holes with the same oxide confined VCSEL is able to convert the multimode operation into a single fundamental mode operation with more than 40 dB SMSR. As apparent from Fig. 1, the threshold currents for the $6 \times 6\ \mu m^2$, $10 \times 10\ \mu m^2$, and PC-VCSEL are 1.3, 2.4 and 3.9 mA, respectively. The increase in threshold current for the PC-VCSEL is caused by the large electrical aperture defined by oxide. If the size of the electrical aperture can be chosen to be similar to the optical aperture, the threshold current of the PC-VCSEL is expected to be close the oxide-confined VCSEL with a same size oxide aperture. The small signal bandwidth of the single fundamental mode from the PC-VCSEL is shown in Fig. 2*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 clamping. The solid line in Fig. 2*a* is a fit to the experimental data at 12 mA injection current using a three-pole approximation of the modulation response equation [12]. From this curve and other fitted curves at different injection currents, the relaxation frequency ($f_r$), rolloff frequency ($f_{par}$) and damping factor ($\gamma$) can be obtained. The *K* factor is calculated to be 0.2 from these values. If parasitic heating effects are ignored, the theoretical maximum 3 dB bandwidth of the PC-VCSEL may be over 40 GHz from the relation $f_{3\ dB} = 2\pi(2)^{1/2}/K$ [12]. The 3 dB bandwidth of the $10 \times 10\ \mu m^2$ oxide aperture VCSEL is more than 11.5 GHz. The emission spectra of the PC-VCSEL under small signal modulation is shown in Fig. 2*b*. Clearly, a single fundamental mode with more than 30 dB SMSR is maintained, although the SMSR is decreased by 10 dB compared to CW operation. It is expected from these data that the PC-VCSEL could operate at 10 Gbit/s under large signal modulation

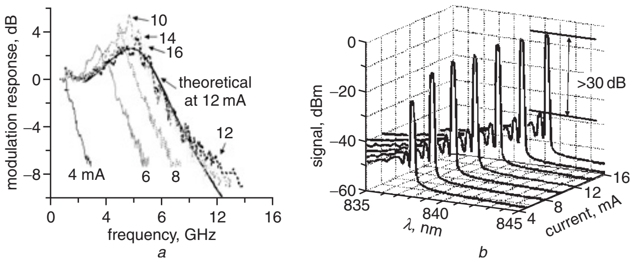


**Fig. 2** *Small signal modulation and emission spectrum at 3 dB frequency at each current of PC-VCSEL*

*a* Small signal modulation *b* Emission spectrum

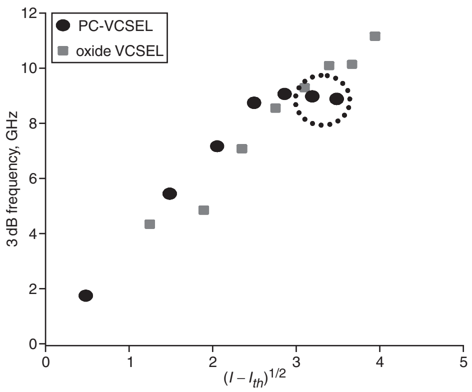


**Fig. 3** *3 dB frequency against* $(I\text{-}I_{th})^{1/2}$ *of PC-VCSEL and oxide-confined VCSEL*

Fig. 3 shows that the modulation current efficiency factor (MCFF) from these devices is similar, ~3 GHz/(mA)$^{1/2}$ when the driving current of the PC-VCSEL is under 12 mA. The result and similar series resistance show that the addition of photonic crystal holes did not introduce serious parasitics harmful to the performance. However, in Fig. 3 the clamping of the 3 dB small signal bandwidth at 9 GHz for an injection current greater than 12 mA observed for the PC-VCSEL, does not occur for the oxide-confined VCSEL. Since an injection current greater than 12 mA is close to the rollover, the 3 dB small signal bandwidth can not increase further. Therefore, the threshold current should be reduced to increase the 3 dB maximum small signal bandwidth of the PC-VCSEL.

*Conclusions:* A PC-VCSEL operating in the single fundamental mode with a record 9 GHz bandwidth at 3 dB frequency is demonstrated for the first time. Emission spectra for CW under DC and small signal modulation confirm single fundamental mode operation. Confinement of the optical mode by modification of the index around a single defect by etched photonic crystal holes provides these improved device characteristics. Further optimisation to reduce the threshold current in design is necessary to improve the modulation performance.

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