Variable reflectance vertical cavity surface emitting lasers

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Singlemode operation in 850 nm vertical cavity surface emitting lasers is reported. The singlemode behaviour results from a radially-varying number of periods in the top distributed Bragg reflector mirror. At the centre of the device there are six additional quarter-wave layers (three periods) as compared to the edge. This provides higher mirror reflectivity to the fundamental mode without adding loss. Thus the top mirror geometry promotes singlemode operation of the laser from threshold to rollover.

Introduction: Vertical cavity surface emitting lasers (VCSELs) are attractive sources for short-distance communications. These lasers operate in a single longitudinal mode, have circular output beams, and can be modulated at high rates. However, it is common for many transverse modes to lase owing to the large diameter and/or strong index confinement caused by the oxide layer in the cavity. By allowing only the fundamental transverse mode to lase, the coupling between VCSELs to singlemode optical fibres can be greatly improved. Fundamental mode operation also has applications in imaging and scanning where a singlemode is desired. For these reasons, many attempts have been made at creating a high-power singlemode VCSEL. Most efforts to obtain greater than 2 mW from singlemode lasing aim at suppressing higher-order modes with some type of loss mechanism. For example, surface relief etching [1–3], photonic crystals [4] or etched wedges [5] may be applied to the top surface of the VCSEL to add loss in the spatial regions of higher-order transverse modes. Some work has also been done to limit the area of the gain to favour the fundamental mode [6]. In this Letter, we use reduced mirror loss along the central axis of the VCSEL to favour the fundamental Gaussian mode. It is expected that this approach should lower the lasing threshold of the fundamental mode with respect to higher-order transverse modes and promote singlemode operation. This approach differs from prior surface relief etching [1–3] because an integral number of distributed Bragg reflector (DBR) mirror pairs are etched. Thus, the higher loss is caused by a reduced mirror reflectivity around the periphery of the VCSEL, but lasing is still possible in these regions. In the case of photonic crystals or wedges etched in the top surface of the VCSEL, the refractive index profile as well as loss is strongly modified [4, 5], which is not the case for the lasers discussed here.

Device description and fabrication: Standard VCSEL growth by metal organic chemical vapour deposition and selective oxidation fabrication techniques are followed [7], with the exception that the uppermost three DBR periods are left undoped. An InGaP etch stop layer is used between these undoped layers and the doped mirror underneath, and an extra photolithography and reactive ion etch step is used to define the mesa at the centre of the device with higher reflectivity. A cross-sectional view of the device is shown in Fig. 1. The bottom *n*-type mirror has 36 periods and the active region contains five GaAs quantum wells emitting at nominally 850 nm. In the top mirror there are 17 *p*-type doped periods and three undoped periods. In Fig. 2, the central region with higher reflectivity is approximately 6 × 6 µm, while the oxide aperture is 5 × 5 µm. The use of the InGaP etch stop layer enables the electrical contact to be precisely placed on a heavily doped layer within the top DBR mirror.

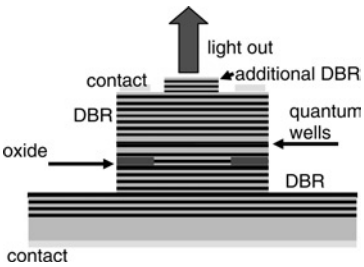

Fig. 1 *Cross-section of variable reflectance VCSEL*

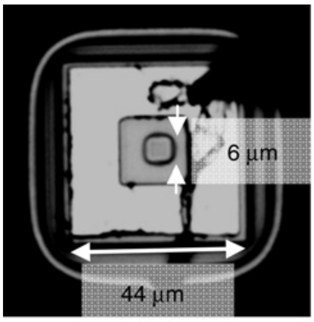

Fig. 2 *Top view of variable reflectance VCSEL*

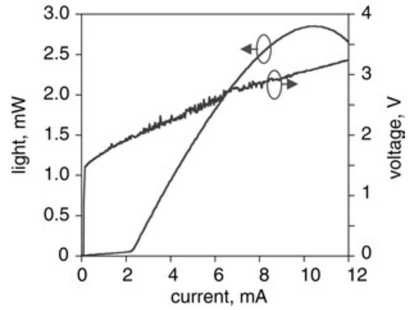

Fig. 3 *Light–current–voltage curve for singlemode variable reflectance VCSEL*

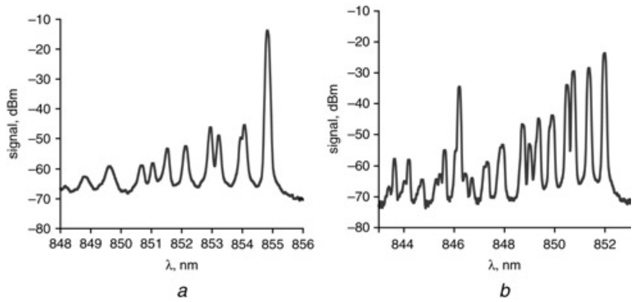

Fig. 4 *Spectra for variable reflectance VCSEL at rollover and multimode oxide VCSEL*

a Variable reflectance VCSEL at rollover
b Multimode oxide VCSEL

Results: A top view of a laser that exhibits singlemode behaviour (>30 dB sidemode suppression) from threshold to thermal rollover is shown in Fig. 2. The light–current–voltage plot in Fig. 3 shows that the device emits nearly 3 mW of power. A spectrum taken at rollover is shown in Fig. 4*a* and shows singlemode operation at rollover. This can be compared to a spectrum in Fig. 4*b* from an oxide VCSEL with a 5 × 5 µm aperture but with the extra three DBR periods in the centre of the device etched away. As expected, the differential quantum efficiency of the multimode device (not shown) is twice that of the singlemode device owing to its decreased output mirror reflectivity (17 periods). Comparing the spectra in Fig. 4 demonstrates that the additional three mirror pairs in the central region of the laser promote the fundamental mode of the device. This in turn allows for single-mode lasing without adding significant loss to the laser. From one-dimensional DBR calculations, it is estimated that threshold gain is decreased by 38% on axis from the three additional DBR periods. Therefore, threshold gain for the fundamental mode is expected to be much lower than that of higher-order modes, consistent with the singlemode operation of the variable reflectance VCSELs. Further optimisation of the relative sizes of the central high reflectivity region with the oxide aperture could potentially lead to greater output power.

Conclusions: It has been shown that altering only the reflectance of the top mirror of a VCSEL such that the fundamental mode has reduced mirror loss compared to higher-order modes results in lasers that exhibit singlemode operation from threshold through thermal rollover.

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References

1 Martinsson, H., Vukusic, J.A., Grabherr, M., Michalzik, R., Jager, R., Ebeling, K.J., and Larsson, A.: 'Transverse mode selection in large-area oxide-confined vertical-cavity surface-emitting lasers using a shallow surface relief', *IEEE Photonics Technol. Lett.*, 1999, **11**, pp. 1536–1538

2 Unold, H.J., Mahmoud, S.W.Z., Jager, R., Grabherr, M., Michalzik, R., and Ebeling, K.J.: 'Large-area single-mode VCSELs and the self-aligned surface relief', *IEEE J. Sel. Top. Quantum Electron.*, 2001, **7**, pp. 386–392

3 Haglund, A., Gustavsson, J.S., Vukusic, J., Modh, P., and Larsson, A.: 'Single fundamental-mode output power exceeding 6 mW from VCSELs with a shallow surface relief', *IEEE Photonics Technol. Lett.*, 2004, **16**, pp. 368–370

4 Yokuchi, N., Danner, A.J., and Choquette, K.D.: 'Two-dimensional photonic crystal confined vertical-cavity surface-emitting lasers', *IEEE J. Sel. Top. Quantum Electron.*, 2003, **9**, pp. 1439–1445

5 Leisher, P.O., Danner, A.J., Raftery, J.J., Siriani, D., and Choquette, K.D.: 'Loss and index guiding in singlemode proton-implanted holey vertical-cavity surface-emitting lasers', *IEEE J. Quantum Electron.*, 2006, **42**, pp. 1091–1096

6 Young, E.W., Choquette, K.D., Seurin, J.-F.P., Chuang, S.H., Geib, K.M., and Allerman, A.A.: 'Comparison of wavelength splitting for selectively oxidized, ion implanted, and hybrid vertical-cavity surface-emitting lasers', *IEEE J. Quantum Electron.*, 2003, **39**, pp. 634–639

7 Choquette, K.D., and Geib, K.M.: 'Fabrication and performance of vertical-cavity surface-emitting lasers' *in* 'Vertical-cavity surface-emitting lasers' (Cambridge University Press, 1999), pp. 193–232