Photonic crystal VCSELs with narrow spectral width and high bandwidth operating at low current density

M. Tan, S.T.M. Fryslie, J.K. Guenter, J.A. Tatum,
R.H. Johnson and K.D. Choquette

A photonic crystal vertical-cavity surface-emitting laser with a spectral width of 0.16 nm and a 3dB small signal modulation bandwidth of 16.2 GHz is demonstrated. Separation of optical and current apertures enables a narrow spectral width and an extremely low operating current density of ~ 1 kA/cm^2 simultaneously. It can potentially be used as a high-reliability laser source that enables error-free transmission over long multimode fibre links at high data rate.

Introduction: Vertical-cavity surface-emitting lasers (VCSELs) in combination with multimode fibres have been widely used as the low-cost solution for short-haul optical data communication [1]. To extend the length of the fibre links with the VCSELs modulated at ever higher data rates for rack-to-rack transmissions in data centres, it is crucial to use VCSELs with narrow spectral width for reduced modal and chromatic dispersion [2]. For oxide-confined VCSELs [3], the common practice is to reduce the optical aperture diameter so that the higher-order modes are cut off, but this comes with the consequence of reduced current aperture size and increased operating current density, which is detrimental to device lifetime [4]. In this Letter we demonstrate a photonic crystal VCSEL with separate optical and current apertures to obtain high modulation bandwidth, narrow spectral width, and low operating current density simultaneously.

Design and fabrication: A photonic crystal in the form of a periodic pattern of air holes etched into the top (output) mirror with one central air hole removed defines the lasing aperture and step-index waveguide condition [5]. The lithographically defined parameters are hole pitch a and hole size b. Compared to oxide-confined VCSELs [3], the index contrast between the cavity and its surrounding is approximately an order of magnitude lower for the photonic crystal VCSELs, therefore the number of transverse modes are greatly reduced. Furthermore, the photonic crystal induces greater optical loss and suppression for the higher-order modes [6]. Current confinement is achieved through proton implantation, with the implant aperture size independently designed.

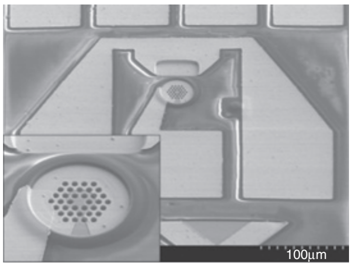

Fig. 1 *Scanning electron microscope image of photonic crystal VCSEL*
Magnified view of mesa and photonic crystal structure shown in lower left corner

The VCSELs contain a top distributed Bragg reflector with 21 $Al_{0.12}Ga_{0.88}As$-AlAs periods and a single-wavelength cavity with three GaAs quantum wells. Device fabrication begins with a plasma-enhanced chemical vapour deposition of silicon oxide (SiO_2) on the wafer surface. Mesa and photonic crystal patterns are transferred to the SiO_2 layer through photolithography. Devices are then implanted with high energy protons, with the implant masks aligned to the centre of photonic crystal patterns. Next, mesas and photonic structures are etched simultaneously with inductively-coupled plasma reactive-ion etching (ICP-RIE) using SiO_2 as the etch mask. Due to aspect ratio scaling of dry etching [7], the mesas can be etched into the bottom mirror but the photonic crystal air holes etching terminates before the active region so that excessive heating due to surface recombination [8] is prevented. Subsequently, lower n- and upper p-contacts are deposited. To facilitate high-speed measurements, the sample is planarised with polyimide and coplanar ground-signal-ground contacts are deposited. A scanning electron microscope image of a completed device is shown in Fig. 1, with a magnified view of the mesa and photonic crystal structure in the lower left corner. Both optical and current apertures are defined with conventional photolithography, hence the VCSELs are manufacturable.

Device characteristics: Fig. 2 shows the light and voltage against current (LIV) curves of a photonic crystal VCSEL with $b/a = 0.7$ and $a = 3.5$ µm. The photonic crystal VCSEL has a low threshold current (I_{th}) of 0.43 mA despite the large nominal implant current aperture of 17.45 µm, due to: 1. strong and stable index guiding from the photonic crystal resulting in low diffraction loss [8], 2. high reflectivity from high index contrast in the mirrors, and 3. an optimised proton implant projected range into the top mirror to reduce lateral current leakage.

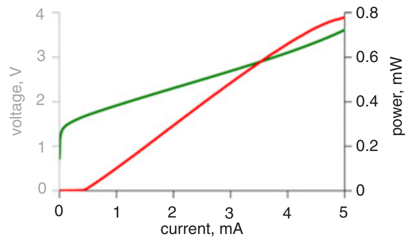

Fig. 2 *LIV of photonic crystal VCSEL with b/a = 0.7 and a = 3.5 µm*

The VCSEL characterised in Fig. 2 is considered quasi-single mode because the side mode suppression ratio between the fundamental and the first higher-order modes is only about 16 dB at an injection current of 5 mA as indicated by the lasing spectrum in Fig. 3. The RMS spectral width as defined by the IEEE 802.3 Standard is 0.16 nm.

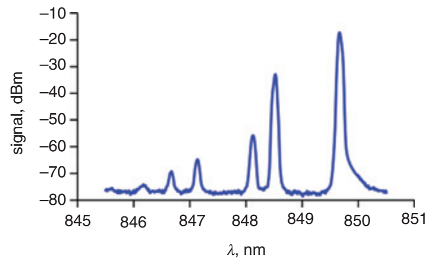

Fig. 3 *Lasing spectrum of photonic crystal VCSEL at 5 mA*

Fig. 4 shows the small signal modulation response curves corresponding to different DC bias currents to the VCSEL (bias currents are 2x, 3x, 4x… threshold current). The maximum 3dB bandwidth of 16.2 GHz is obtained at 3 mA corresponding to roughly seven times the threshold current. By taking the nominal implant aperture of 17.5 µm, the resultant operating current aperture is < 1.3 kA/cm^2, which is almost an order of magnitude lower than the benchmark for the high-reliability operation regime [4].

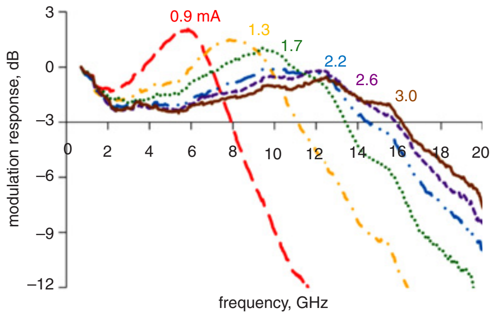

Fig. 4 *Small signal modulation response curves corresponding to different DC bias currents to photonic crystal VCSEL*

The 3dB frequency is plotted against $(I - I_{th})^{1/2}$ in Fig. 5. The slope of the linear portion of the curve is defined as the modulation current efficiency factor (MCEF) [9]. The MCEF for this photonic crystal VCSEL is 12 GHz/mA$^{1/2}$, which is higher than those typically reported for oxide VCSELs with GaAs quantum wells [10]. This can be attributed to the high internal quantum efficiency of the active region as well as the high index contrast in the mirrors and the single mode photonic crystal cavity which reduces the mode volume.

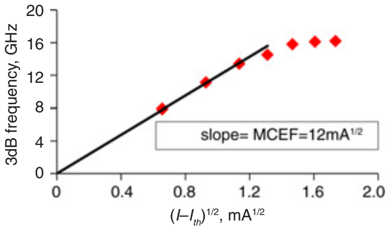

Fig. 5 *3dB frequency plotted against* $(I - I_{th})^{1/2}$

Slope of linear portion of curve defined as the MCEF

Conclusion: Due to separation of the optical and current aperture, photonic crystal VCSELs enable narrow spectral width and low operating current density simultaneously. The optimised epitaxial design of the wafer facilitates low threshold current and a high modulation current efficiency factor, whereas the photonic crystal structure provides effective optical confinement for small modal volume. With a narrow spectral width of 0.16 nm and a maximum 3dB bandwidth of 16.2 GHz obtained at 1.3 kA/cm^2, these devices are compatible for VCSEL-based data communication at high data rate while operating at a high-reliability bias regime.

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One or more of the Figures in this Letter are available in colour online.

M. Tan, S.T.M. Fryslie and K.D. Choquette (*Department of Electrical and Computer Engineering, University of Illinois, 208 N. Wright Street, Urbana, IL 61801, USA*)

E-mail: mengtanuiuc@gmail.com

J.K. Guenter, J.A. Tatum and R.H. Johnson (*Finisar, 600 Millennium Drive, Allen, TX 75081, USA*)

References

1 Pepeljugoski, P. *et al.*: 'Development of system specification for laser optimized 50-μm multimode fiber for multigigabit short-wavelength LANs', *J. Lightwave Technol.*, 2003, **21**, (5), pp. 1256–1275

2 Freund, R. *et al.*: 'High-speed transmission in multimode fibers', *J. Lightwave Technol.*, 2010, **28**, (4), pp. 569–586

3 Choquette, K.D. *et al.*: 'Low threshold voltage vertical-cavity lasers fabricated by selective oxidation', *Electron. Lett.*, 1994, **30**, (24), pp. 2043–2044

4 Hawkins, B.M. *et al.*: 'Reliability of various size oxide aperture VCSELs'. Proc. 52nd Electronic Components and Technology. Conf., San Diego, CA, USA, 2002, pp. 540–550

5 Yokouchi, N., Danner, A.J., and Choquette, K.D.: 'Two-dimensional photonic crystal confined vertical-cavity surface-emitting lasers', *J. Sel. Top. Quantum Electron.*, 2003, **9**, (5), pp. 1439–1445

6 Siriani, D.F., Leisher, P.O., and Choquette, K.D.: 'Loss-induced confinement in photonic crystal vertical-cavity surface-emitting lasers', *J. Sel. Top. Quantum Electron.*, 2009, **45**, (7), pp. 762–768

7 Gottscho, R.A., and Jurgensen, C.W.: 'Microscopic uniformity in plasma etching', *J. Vac. Sci. Technol. B*, 1992, **10**, (5), pp. 2133–2143

8 Tan, M., Kasten, A.M., Sulkin, J.D., and Choquette, K.D.: 'Planar photonic crystal vertical cavity surface emitting lasers', to appear in *J. Sel. Top. Quantum Electron.*, 2013, **19**, (4).

9 Chen, T.R. *et al.*: 'Very high modulation efficiency of ultralow threshold current single quantum well InGaAs lasers', *Electron. Lett.*, 1993, **29**, (17), pp. 1525–1526

10 Westbergh, P. *et al.*: 'High-speed, low-current-density 850 nm VCSELs', *J. Sel. Top. Quantum Electron.*, 2009, **15**, (3), pp. 694–703