In-phase, coherent photonic crystal vertical-cavity surface-emitting laser arrays with low divergence

D.F. Siriani and K.D. Choquette

Two-dimensional vertical-cavity surface-emitting laser (VCSEL) arrays are defined using an etched photonic crystal pattern and ion implantation. The 2 × 2 laser arrays are shown to operate in a single in-phase mode from threshold to maximum output power. The in-phase interference between the multiple lasers constituting the array form an angularly narrow, on-axis peak in the far field. These coherently-coupled laser arrays are of interest owing to their ease of fabrication and potential for creating low-diffraction beams with increased output power.

Introduction: Two-dimensional vertical-cavity surface-emitting laser (VCSEL) arrays are of interest for applications in communications, sensing, and high power optical applications owing to their low cost and relatively simple fabrication. Unfortunately, coherently-coupled index-guided VCSEL arrays typically operate in an out-of-phase mode as a result of inter-element loss introduced by mirror etching [1, 2] or metal contacts [3–5] in the coupling region. To circumvent this problem, phase-adjusted [6], anti-guided [7–9], and implant-defined [10] arrays have been demonstrated. The phase-adjusted and leaky mode arrays, however, typically require complicated fabrication procedures, while implant-defined arrays tend not to have stable mode control above threshold.

An alternative method for defining two-dimensional arrays has been to use a photonic crystal with a modified pattern in the coupling region [11, 12]. This approach to date has relied exclusively on the photonic crystal to provide optical confinement between elements. The etched holes can introduce inter-element loss, which causes preferential excitation of the out-of-phase mode. For this reason, in-phase operation is achieved only with special photonic crystal patterns and limited consistency [12]. In this Letter, we report on VCSEL arrays that incorporate a photonic crystal to provide stable index confinement [13] combined with proton implantation to pixellate the gain region and define the array elements.

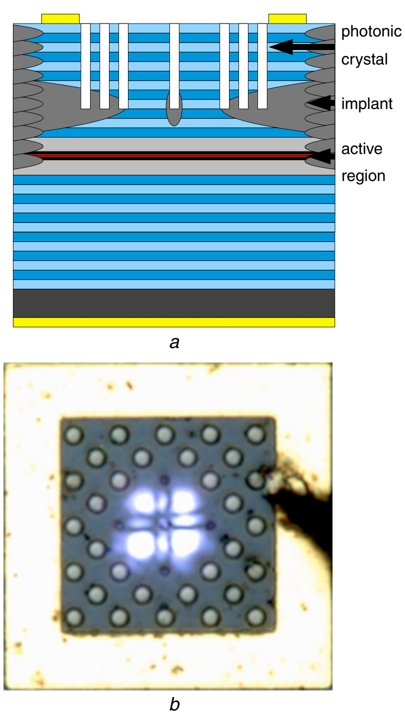

Fig. 1 *Cross-sectional sketch of photonic crystal implant-defined VCSEL array, and 2 × 2 square-lattice photonic crystal array while lasing*

a Photonic crystal implant-defined VCSEL array
b 2 × 2 square-lattice photonic crystal array while lasing

VCSEL design and performance: A cross-section of the basic device design is shown in Fig. 1*a*. The fabrication procedure is identical to that in [10] except with the addition of an inductively-coupled plasma reactive-ion etch for the photonic crystal holes. The devices studied are 2 × 2 laser arrays defined by a square photonic crystal lattice. The periods of the photonic crystals are either 5.5 or 6 μm, and the diameter-to-period ratios are 0.6 or 0.7 for both photonic crystal periods. The lack of an air hole directly between elements reduces the amount of loss introduced into this region by the photonic crystal, which allows sufficient gain for the in-phase mode to lase [12]. Simultaneously, the photonic crystal provides stable index guiding. To further reduce the inter-element loss, the photonic crystal holes in the coupling region also can be reduced in size, as shown in the device in Fig. 1*b*.

Multiple 2 × 2 arrays with these design parameters, particularly those with a reduced coupling-hole size, tend to lase in a single in-phase mode. A typical device with good single-mode characteristics is presented in Fig. 2. This device has a photonic crystal period of 6 μm, a diameter-to-period ratio of 0.6, and a coupling-hole ratio reduced to 0.3. The unimplanted regions are square apertures with approximate side length of 6.5 μm and nearest neighbour centre-to-centre separation of 8.5 μm. Fig. 1*b* shows a near-field image of this device while lasing. Fringes in the near field can be seen between the array elements, indicative of in-phase lasing.

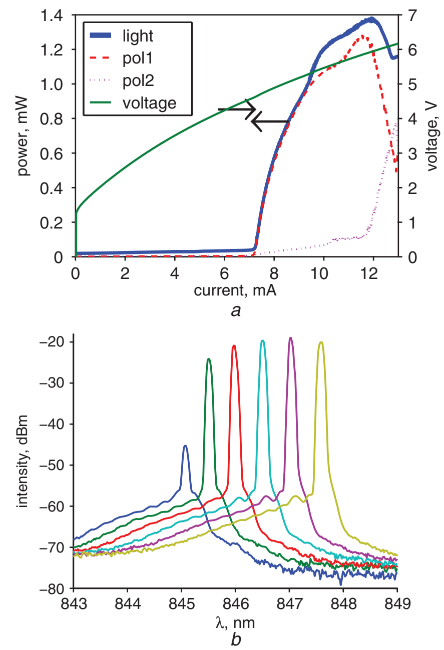

Fig. 2 *LIV characteristic of single-mode, in-phase 2 × 2 array with polarisation data, and single-mode spectra taken at 7.1 to 12.1 mA in 1 mA steps*

a LIV characteristic
b Single-mode spectra

Threshold current of this array is 7.1 mA, and the maximum output power is 1.4 mW. The laser array operates with a higher series resistance owing to lateral resistance introduced by the implant damage near the surface of the laser [14]. Kinks are apparent in the light-intensity (LI) plot in Fig. 2*a*. However, they are not a result of other modes turning on as can be seen by the single spectral peak in the laser emission shown in Fig. 2*b*. Polarisation data (total powers are estimated to compensate for polariser loss) are included in the LI plot, showing also that one polarisation dominates. The linear polarisation is aligned along the diagonals of the square formed by the four elements, although polarisation rotated 45° from that is also observed. It is unclear as to the mechanism of polarisation control, although it has been suggested that the square-lattice photonic crystal has an influence [15].

The laser array operates in-phase, as can be seen from the on-axis maximum in the far-field beam patterns shown in the inset of Fig. 3. At all currents, the same radiation pattern is apparent, with a central peak surrounded by eight subsidiary lobes. The distinguishing characteristic between lower and higher current injection is that the power in the outer lobes decreases as the injection current increases, as seen in Fig. 3. The power in the central lobe reaches approximately 20%, which corresponds to 1.5 times more power in this lobe than in any subsidiary lobe.

Additionally, the angular divergence of the central lobe is much less than that of a conventional VCSEL. In the inset of Fig. 3, for example, the full-width half-maximum (FWHM) along a vertical cut of the central lobe is 2.7°. In general for these 2 × 2 coupled arrays, the FWHM is between 2.5° and 3.5°. In comparison, regrown leaky mode 2 × 2 VCSEL arrays produced approximately a 3° divergence [16].

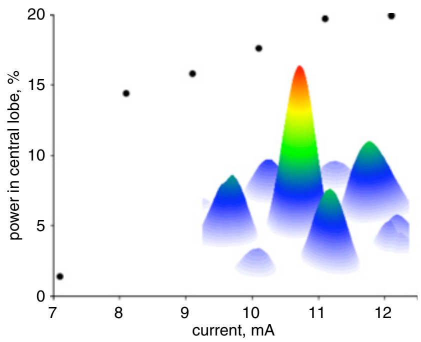

Fig. 3 *Percentage of total power contained in central lobe of far field for different injection currents*

Inset: 3D view of far-field radiation pattern taken at rollover

Conclusion: We have described 2 × 2 coherent VCSEL arrays using hybrid ion-implantation and photonic crystal confinement. These laser arrays operate in-phase, producing a low-divergence, on-axis beam in the far field. Moreover, these coupled lasers operate on only this single mode from threshold to maximum power. With this knowledge and by addressing the issue of uniform current injection, it should be possible to scale these arrays to larger sizes for increased power and decreased angular divergence.

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

D.F. Siriani and K.D. Choquette (*Micro and Nano-technology Laboratory, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*)

E-mail: siriani@illinois.edu

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