Coupled-defect photonic crystal vertical cavity surface emitting lasers

A.J. Danner, J.C. Lee, J.J. Raftery, Jr., N. Yokouchi and K.D. Choquette

Photonic crystal patterns containing two defects were fabricated within a large gain area in vertical cavity surface emitting lasers. By designing effective refractive index changes in the region between the defects through cavity shifts caused by photonic crystals, it was possible to coherently couple laser light output from the defects. This enables a novel way to fabricate coherently coupled laser arrays.

Introduction: Because of limitations in achieving high power single-mode characteristics in single vertical cavity surface emitting lasers (VCSELs), coherently coupled laser arrays offer one option to increase singlemode output power. Previously, coherent arrays have been fabricated using mirror reflectivity modulation, or cavity or phase modifications to achieve coupling between adjacent elements in vertical structures [1–4]. We propose using two-dimensional photonic crystals to delineate a coherent VCSEL array, with individual defects (the absence of photonic crystal holes) creating the lasing elements. In this case, the lasing array is wholly contained within the same unpixelated gain area.

Coherent laser arrays have been demonstrated previously using positive index guides and evanescent coupling, both with edge emitting lasers [5] and two-dimensional VCSEL arrays [1–3]. Because of difficulties in achieving a main on-axis lobe (in-phase coupling) with positive index lasing sites, leaky mode coupling between array elements has also been achieved in edge emitting lasers [6] and VCSELs [4, 7]. Both techniques involve either the raising or lowering of the effective index of lasing regions compared with coupling regions. Since cavity resonance shifts have been shown to yield effective index changes [8], the slight shifts caused by photonic crystals can be used to induce small index changes [9] useful in producing coherently coupled arrays.

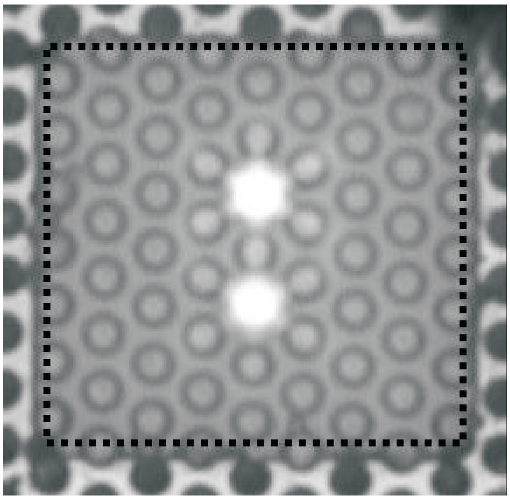

Fig. 1 *Near-field image of photonic crystal VCSEL with two defects lasing in their fundamental modes*

Dotted line indicates 25 µm wide oxide aperture

The type of photonic crystals created within the VCSELs are similar to those in photonic crystal fibres [10] and do not rely on an in-plane bandgap for their operation. Rather, they approximately create a positive index waveguide region at each defect site, with the equivalent index step tightly controlled by the design parameters of the photonic crystal array, which in our case is a periodic array of etched holes [9]. Singlemode operation is possible when the design allows only one defect mode to propagate because of the wavelength dependence of the equivalent refractive index [10, 11]. This is one distinguishing feature of photonic crystal VCSELs as opposed to reflectivity-modulated VCSELs, where modal discrimination is achieved through loss mechanisms. Controlled singlemode operation has been reported from VCSELs containing a single photonic crystal defect [11, 12], as well as reduced scattering loss compared to selectively oxidised VCSELs [13].

Device description: A two-dimensional triangular lattice array of holes was etched into VCSELs with 25 µm wide oxide apertures using inductively coupled plasma etching, the holes themselves having been first lithographically defined with focused ion beam etching into a SiO_2 mask. The hole spacing was 4.6 µm and the hole diameter-to-lattice constant ratio was 0.7. The hole depth was measured to be approximately 15 pairs of the top distributed Bragg reflector, which contains 25 pairs total. The VCSELs were selectively oxidised devices lasing nominally at 850 nm and were characterised prior to the addition of the photonic crystal holes. Fig. 1 shows a near-field image of a device with each single defect cavity lasing in its fundamental photonic crystal defect mode. A metal contact ring surrounds the oxide aperture for current injection. In this study, only two single defect cavities were created by the absence of two holes near the centre of the device. The photonic crystal VCSELs are electrically injected and operate continuous wave at room temperature.

Measurements: Far-field measurements were carried out using a pinhole detector placed at a fixed height above the sample. Intensity measurements at periodic distances along the transverse axis of the device were taken. For the case of coupled defects, we expect a coherent mode of the array to be evident in the far field by virtue of an on-axis null for out-of-phase coupling (or maximum, for in-phase coupling) with sidelobes and for uncoupled defects a simple intensity addition of two Gaussian beams should be observed.

Fig. 2 shows far-field measurements on two devices, (i) where the central hole between the two defects is 3.2 µm in diameter, and (ii) where the central hole is 2.3 µm in diameter. The centres of the defects are separated by two lattice constants of the photonic crystal array. The etching depth of the 2.3 µm hole is also slightly shallower because the devices were etched at the same time and a smaller hole diameter leads to a reduced etch rate. For device (i), the far-field intensity profile is consistent with out-of-phase coherent coupling. By controlling the coupling regions (holes) between the defects, it should be possible to fabricate larger arrays of photonic crystal defect coupled arrays. Unlike leaky-mode coupling reported where there is modal loss outside the antiguide [4, 6], the photonic crystal defects are evanescently coupled.

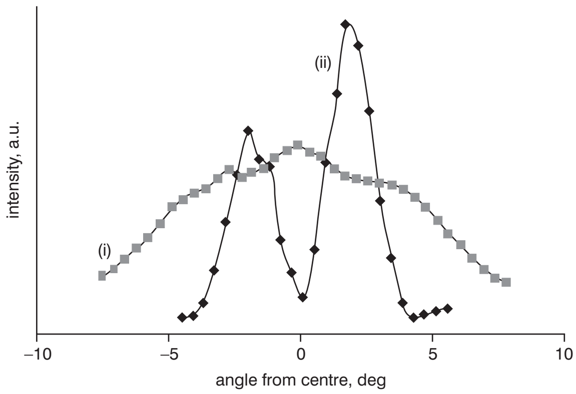

Fig. 2 *Far-field intensity profiles for uncoupled and coupled defects*

Scans were in vertical direction along central axis
(i) Uncoupled defects (ii) Coupled defects

We further note that in the case of coupled defects, lasing for each defect occurs at the same threshold current and wavelength, whereas uncoupled defects lase at slightly different thresholds and wavelengths. This is because they are distinct devices, even though they are in the same gain area with approximately the same current injection. This is illustrated in Fig. 3, which shows spectra obtained for the uncoupled-defect device (Fig. 3*a*) and a coupled-defect device (Fig. 3*b*). The spectrum in each case represents a device well above threshold, with both defects lasing. The marked difference in the spectra between the two show that in the coupled case (Fig. 3*b*), both defects lase at the same wavelength and are locked together with increasing current. In the uncoupled case (Fig. 3*a*), the lasing wavelength of the defect with lower threshold began red-shifting before the other defect began lasing as current was increased. This presumably causes the wavelength separation seen in Fig. 3*a*.

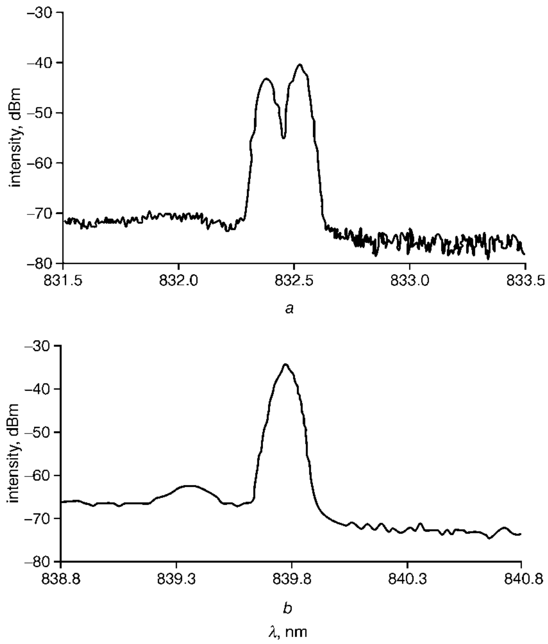

Fig. 3 *Lasing spectra for uncoupled and coupled defects*
a Uncoupled defects *b* Coupled defects

Conclusions: Coupled photonic crystal defect lasers have been fabricated and characterised in electrically-injected VCSELs. Far-field measurements indicate that controlling the coupling can be achieved by locally modifying the hole diameter in the photonic crystal array between the defects to be coupled. We are presently studying designs to achieve in-phase coupling, which may produce less excess loss than those of other mirror modification techniques or by leaky-mode coupling.

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