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Final Report: Photonic Crystal Light Emitting Laser Arrays

ABSTRACT

Coherently coupled arrays of vertical cavity surface emitting lasers (VCSELs) offer the potential of extended area coherent sources useful in a variety of applications in the high power (laser radar, optical communications, steerable sources) and low power (image processing, spectroscopic sensing, optical logic) regimes. A recently developed method for providing optical confinement is the introduction of a two-dimensional photonic crystal (PhC) pattern with a defect, etched into the top distributed Bragg reflector, to define a defect cavity in a VCSEL. This report investigates the operation of PhC VCSELs that have multiple defect cavities to form arrays of vertically emitting lasers. A major achievement of this work is coherent coupling between the defect cavities, with both out-of-phase and in-phase coherent coupling in   and   defect cavity arrays. A qualitative and quantitative understanding of the optical characteristics of PhC VCSEL arrays was developed and demonstrated by the agreement of simulated to experiment results. Other conclusions supported by this study are: (1) different wafers result in coupling at different overlap integral values; (2) coupling can be effected by thermal effects (hysteresis observed), and (3) the relative phase difference between the defect civilities can be varied with injection current during both continuous-wave and pulsed operation.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

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K. D. Choquette, A. J. Danner, and J. J. Raftery, Jr., "Photonic Crystal Vertical Cavity Lasers" (invited), 9th Optoelectronic and Communications Conference, Yokohama, Japan (July 2004).

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K. D. Choquette, A. J. Danner, J. C. Lee, J. J. Raftery "Vertical Cavity Photonic Crystal Coupled-Defect Lasers" Microelectronics, MEMS, and Nanotechnology Conference, Perth, Australia (Dec. 2003).

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(d) Manuscripts

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Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED	
Aaron Danner	0.25	No
FTE Equivalent:	**0.25**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Kent Choquette	0.00	No
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
Lt. Col. James Raftery, Jr.	No

Total Number: **1**

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Final Report: Photonic Crystal Vertical Cavity Laser Arrays

Statement of Problem:

  Vertical cavity surface emitting lasers (VCSEL)s have several features such as low threshold, high beam quality, and low cost, which make them attractive for many applications. Because of their vertical out-of-the-epitaxial-plane light emission, VCSELs are uniquely suited for arrangement into 2D arrays. Individually addressable 2D arrays of uncoupled VCSELs are potential emitters for high speed optical interconnects, such as chip-to-chip and board-to-board communications. An individually addressable 8x8 array of VCSELs was first reported in 1991 [1]. However, it is their potential utilization in coherently coupled arrays that is directly analogous to the work undertaken herein.

  The first demonstration of such a phase-locked 2D array was reported in January 1990 by Yoo et al. [2]. This array was comprised of more than 160 VCSELs etched 1.3 μm in diameter, with a spacing of less than 0.1 μm between each lasing element. The overall array was 25 μm in diameter and each of the lasers was located on a 2D rectangular lattice, which allowed evanescent optical coupling between the device elements. The array produced a double-lobed beam pattern in the far field. That same year a reflectivity modulation technique was employed to produce an optically coupled 3x3 2D array of VCSELs, which also produced a double-lobed far field pattern [3].
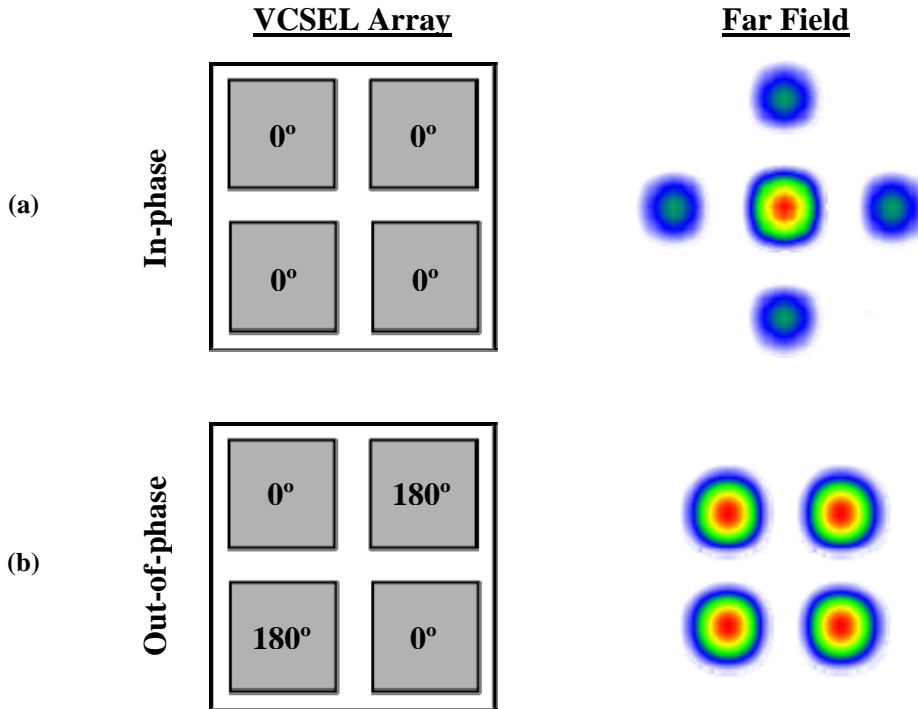
VCSEL Array   **Far Field**

Figure 1: Graphical depiction of the results described by Hadley [33], for VCSEL arrays in the coherently coupled (a) in-phase and (b) out-of-phase cases. Shown at the left are gray boxes representing the top-down view of a 2×2 arrangement of VCSELs with relative phase angles labeled for the in-phase and out-of-phase cases, respectively. Also shown is a qualitative depiction of the resulting far field radiation pattern indicative of in-phase and out-of-phase coherent coupling, respectively.

Shortly thereafter, Hadley introduced a formalism for the investigation of optical modes of 2D phase-locked VCSEL arrays [4]. He described a fundamental and higher order evanescent mode for the case where VCSEL array elements are separated by material of lower refractive index. He also described a fundamental and higher order "leaky mode" for the case where VCSEL array elements are separated by material of higher refractive index. Because this case is not applicable to the work conducted herein, discussion will be limited to the evanescently coupled case. The fundamental mode arrangement has adjacent emitter elements of the array that are in-phase with each other; that is, the elements have zero relative phase difference. For the higher order modes, the adjacent elements are out-of-phase with each other; that is, they have a relative phase difference of 180°.

Figure 1 shows a qualitative depiction of the phase relationship between adjacent elements in an extended array of individual VCSEL elements as used in the calculations by Hadley, illustrating this point. For the parameters of his calculations, Hadley concluded that in the evanescent coupling case, the higher order mode would have lower loss than the fundamental mode, where the lowest loss mode is likely the mode that would occur at threshold. He also made predictions for the 2D far field profiles. The fundamental mode in the 1D array case (line array of devices) is characterized by a single on-axis lobe accompanied by two smaller side lobes. Hadley predicted that for the 2D array case, the fundamental mode should result in a central peak surrounded by four lesser side lobes, as is illustrated graphically in Figure 1(a). For the higher order case, the far field intensity pattern of the 1D array having two identical off-axis peaks is replaced in the 2D array case by a pattern with four nearly equal off-axis peaks, as seen in Figure 1(b). Hadley concludes that gain-guided and most index-guided 2D arrays are likely to lase in the higher order (out-of-phase) mode with their radiation emitted into four equal intensity far field peaks. Since in-phase coupling is the result most appropriate for the applications of extended area coherent sources listed earlier, Hadley's results indicate that realizing in-phase coupling in evanescently coupled devices may not be easily achieved.

To investigate these results, Warren et al. [5] fabricated 2D coherent VCSEL arrays which employed a reflectivity modulation scheme and added an integrated phase corrector in every other element in the VCSEL array. The far field pattern for the uncorrected 2D array indeed showed the four off-axis lobes predicted by Hadley, indicative of out-of-phase coherent coupling. The phase corrected array produced a far field pattern with a central on-axis lobe and four side lobes, analogous to in-phase coherent coupling. In this case, the out-of-phase coupling was converted into in-phase coupling by the intermeshed 180°-phase shifter elements. However, this result was achieved at the expense of a very difficult fabrication process.

In 1999 a two-element phased array of antiguided VCSELs was first reported [6]. The lateral index modification required for antiguiding was achieved by modification of the cavity length in the microcavity. This required a patterned 3-nm etch performed between two epitaxial growths. Both in-phase and out-of-phase operation were achieved by varying the separation between lasing elements. In 2000, this work was extended to 4x4 arrays of in-phase and out-of-phase coherently coupled antiguided VCSELs [7]. Actively controlled methods for injection locking arrays of VCSELs through the use of a "leader" laser to seed the mode of "follower" array elements in order to achieve coherent coupling has also been demonstrated to achieve both in-phase and out-of-phase coherent coupling as observed in the far field [8].

Our initial investigations into PhC VCSELs with multiple PhC defect cavities showed some promising results for achieving coherent coupling between multiple lasing elements, and motivated the continued work that will be described herein. Shown in Figure 1.10 is the near

field image of a PhC VCSEL with a two lasing defect cavities. Shown in Figure 2 is the first reported example of coherent coupling between multiple defect cavities in a PhC VCSEL [9]. The far field intensity profile from the device in Fig. 2 shown is categorized as coherently coupled because of the interference effects that are exhibited in the far field. The result is consistent with that described by Hadley as out-of-phase coherently coupled as two main lobes with an on-axis null are observed.
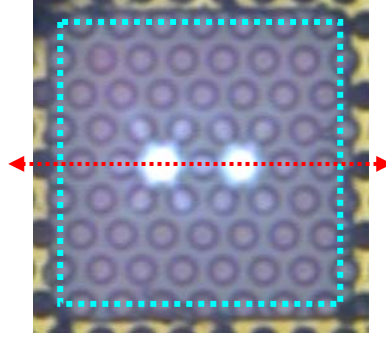

Figure 2: Near field image of a PhC VCSEL with multiple defect cavities each lasing in its fundamental mode. The dashed square denotes the location of the 25-µm wide oxide aperture. The red line indicates the line scanned during far field measurements [38].

The scope of the work is to investigate PhC VCSELs operating with multiple defect cavities. Studies are conducted to investigate the PhC parameter space with the goal of achieving coherent coupling between multiple defect cavities, and more specifically, in-phase coherent coupling. Devices are fabricated and characterized. The major focus of the effort will be to develop a qualitative and quantitative understanding of the measured results.

A PhC design with the cross section of the resulting multiple defect cavity PhC VCSEL is shown in Figure 3(a) and (b), respectively. The region between the defects is denoted as the coupling region. The index of this region between the lasing cavities is expected to be less than
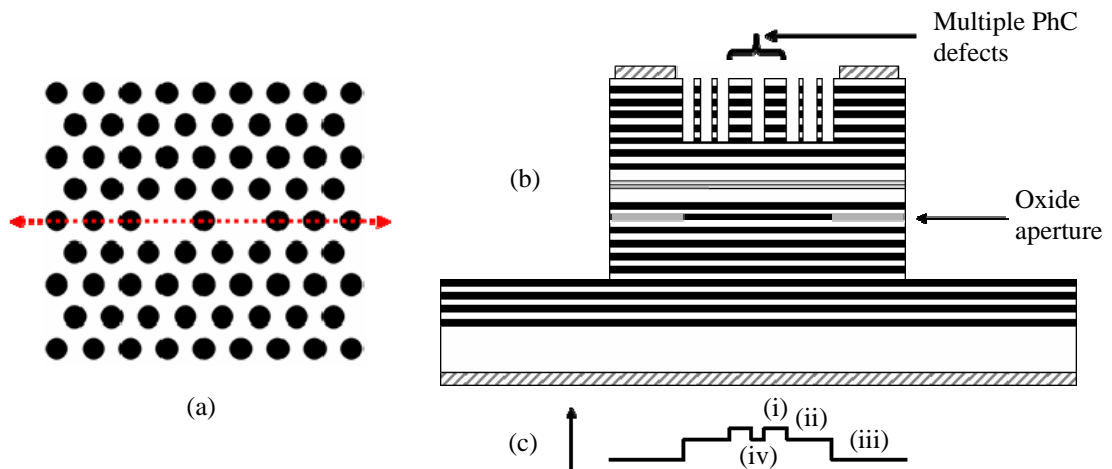

Figure 3: (a) Top view of a PhC pattern with multiple defects. The red arrow indicates the slice shown in (b) the side view cross section of a multiple defect cavity PhC VCSEL. (c) Indicates the corresponding change in effective index seen in the structure (not drawn to scale).

3

that of in the defect cavity (i), but higher than that in the PhC region (ii). It is expected that by varying the parameters of the PhC air hole or holes in the coupling region, changes to the index in the coupling region can be realized and the result will allow coherent coupling over some range of design parameters. In addition to the change in index, the parameters of the holes in the coupling region will also have an impact on optical loss.

Summary of Most Important Results

In this research, an investigation of vertical cavity surface emitting lasers operating with multiple photonic crystal defect cavities has been described [10-13]. A 2×1 defect cavity coherent coupling study was conducted for four different types of 2×1 defect cavity orientations, each with systematically varied coupling region PhC hole diameters, encompassing 100 total devices. Fabrication resulted in a 95% device yield, meaning that only five of the devices in the study did not achieve simultaneous lasing in each of the PhC defect cavities. Far field intensity profiles were measured as a method to determine coherent coupling. The study showed that 75% of the devices produced coherent coupling as manifested by the far field characteristics. These results were compared to the overlap integral calculations and the trend predicted by the simulations was clearly observed in the measured data. Furthermore, the goal of achieving in-phase coherent coupling within the parameter space defined for the study was achieved and explanations for this result were offered.

A limited number of 2×2 defect cavity PhC VCSEL devices were also fabricated and studied. Discontinuities in the light vs. current characteristics were definitively explained. Both out-of-phase and in-phase coherent coupling were observed in these 2D array devices. The achievement of in-phase coherent coupling will likely enable new applications for VCSEL arrays. Finally, a major focus of this work was to develop a qualitative and quantitative description for the observed near and far field modes of coherently coupled devices, as demonstrated by the matching to measured results. This was accomplished for both the in-phase and out-of-phase cases in 2×1 and 2×2 arrangements of PhC defect cavities. These simulation tools will provide the design infrastructure to enable further optimization of in-phase coherent VCSEL arrays.

Coherently Coupled Out-of-Phase VCSEL Arrays [10]

Selectively oxidized 850 nm VCSELs, created with a mesa etch fabrication process [14], were fabricated and characterized prior to being modified into PhC VCSELs. The top n-type DBR contains 25 mirror periods. There is a single AlAs layer located in the p-type lower DBR, which when oxidized, resulted in a square oxide aperture approximately 25 μm on each side. Au-Ge/Ni/Au was evaporated to create a topside metal contact ring for each device, while Ti/Au was used as the common backside metal contact. To create the PhC VCSELs, a layer of SiO$_2$ was deposited over the surface of the sample. A 2D triangular lattice of holes was then patterned through the SiO$_2$, using focused ion beam etching, with the multiple defect cavities designed into the photonic crystal lattice by omitting selected holes. The pattern was then etched approximately 15 periods into the top DBR of the VCSEL using inductively coupled plasma reactive ion etching, thereby creating the air holes.

A series of devices with a PhC lattice containing a 2x2 defect cavity pattern was fabricated. Parameters of the PhC lattice (lattice constant, hole diameter, and hole depth) were chosen to give single mode operation in a single defect case [15]. The lattice constant was 4.0 μm and the hole diameter-to-lattice constant ratio was 0.7. Figs. 2 and 3 show examples of

patterns that were etched into the devices. In successive devices, the diameters of the four innermost holes, which are within the coupling regions between defect cavities, were reduced. Reduction in hole diameter is accompanied by a reduction in hole depth, relative to the other holes in the PhC lattice, due to reactive ion etch loading effects. Modifying these selected holes allows precise control of the effective index in the coupling regions, while positioning the optical loss to the location of the holes. Using this technique for controlling effective index between defect cavities differs from etching trenches or reflectivity modulation to define array elements because optical loss need not be introduced across the entire coupling region. In the series of fabricated devices shown in Fig. 1, the reduction of hole diameter and depth results in increasing the effective index in the coupling regions and reducing the optical loss.

Due to the geometry of the 2D triangular lattice used, there are asymmetries in the positioning of the 2x2 defect cavities. For a lattice constant a, the distance between the centers of the two top (or bottom) defect cavities is $2a$, which in this case is 8.0 µm. The distance between the centers of the two left (or right) defect cavities is equal to $\sqrt{3}\,a$, which in this case is 6.9 µm. Additionally, there are asymmetries in the coupling regions between the defect cavities. The coupling regions between the two top (or bottom) defect cavities has an air hole directly between the centers of the defect cavities, while the coupling regions between the two left (or right) defect cavities has a gap. There is also a potential coupling region in the area at the center of the four defect cavities. As the diameter of the four holes in the coupling region is reduced, the unetched area within this central coupling region increases until it is a substantial fraction of the area of a defect cavity, and eventually results in an additional optical cavity.

Fig. 4 shows the near field lasing pattern of a 2x2 PhC VCSEL. This image shows four distinct lasing cavities, each confined within a defect cavity in the PhC lattice. The threshold current value for this device is 15 mA, approximately twice that of the broad area oxide VCSEL prior to etching the PhC lattice. This increase is attributed to optical loss resulting from the etched holes. For the oxide VCSEL, the optical and electrical
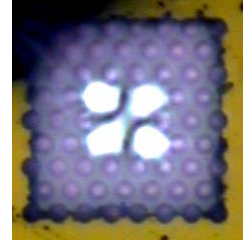

Fig. 4 Near field of 2x2 array

apertures coincide with the oxide aperture. Each defect cavity has an area of approximately 50 µm^2, for a combined area of 200 µm^2, compared with 625 µm^2 for the oxide VCSEL without the PhC lattice. For this reason, much of the injected current passes through areas of the electrical aperture that do not coincide with the optical apertures, and subsequently does not contribute to stimulated emission. Designing the optical aperture to be closer in size to the electrical aperture has lead to the reduction of threshold and increased output power in single defect cavity devices.[12]

Fig. 5(a)-(c) shows far field images (to scale relative to each other) taken just above threshold from the 2x2 PhC VCSEL arrays. From these images, a determination of incoherent (uncoupled) or coherent coupling between the 2D array of defect cavities can be made. Fig. 5(a) and 5(c) are examples of devices which are not coherently coupled, with far fields indicative of the superposition of the Gaussian-like beams emitted from each of the operating defect cavities. Fig 5(b), however, shows a far field image consistent with out-of-phase coherent coupling between the 2x2 array of defect cavities [4]. The out-of-phase condition for the 2x2 array arises when a diagonal pair of defect cavities has the same phase, but is 180º out-of-phase with the other diagonal pair of defect cavities. While the far field image of Fig 5(b) is an example of out-of-phase coherent coupling, there are features in the pattern that are not explained by simply having identical lasing defect cavities with an out-of-phase phase relationship. These features

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include the larger, brighter lobes at the top-right and bottom-left, and an elliptical-shape of each lobe. To investigate these features, simulations of coherent coupling for the PhC VCSEL were performed using a beam propagation method. The PhC lattice of air holes was placed within a background material with refractive index 3.3, comparable to the effective index of the VCSEL within the oxide aperture. Circular Gaussian sources of identical shape and intensity were centered below each defect aperture having the fixed out-of-phase phase relationship described earlier, and the beams were allowed to propagate through the material for a distance of 5 μm.

(a)   (c)

(b)   (d)

Figure 5. Far field images taken just above threshold from the 2x2 PhC VCSEL array. Both (a) and (c) are examples of uncoupled devices with far fields indicative of the superposition of the Gaussian-like beams from each of the operating defect cavities, (b) is indicative of out-of-phase coherent coupling, and is taken from the device of Fig. 4. (d) Simulation of the far field radiation pattern for the device of Fig. 4, operating coherently out-of-phase.

The simulation resulted in images which were generally consistent with the near field shown in Fig. 4 and with the far field of Fig. 5(b), though the far field lobes were more symmetric, not exhibiting the features mentioned above. Examination of the measured near field profiles, shown in the inset of Fig. 4, shows that the centroids of the lasing beams are not exactly centered within the defect apertures. By adding this into the simulation, a far field image was calculated and is shown in Fig 5(d). This image now exhibits larger, brighter lobes at the top-right and bottom-left, and is in good agreement with the image of Fig. 5(b). Through further simulation it was determined that the elliptical-shape could be explained by increasing the intensity of one of the Gaussian sources relative to the other three. Such an occurrence could physically arise from greater current injection into one of the defect cavities caused by a slight misalignment of the oxide aperture and photonic crystal pattern.

Coherently Coupled In-Phase VCSEL Arrays [12]

In-phase coherent coupling for both 2×1 and 2×2 arrays of defect cavities in PhC VCSELs have been demonstrated. The arrays were fabricated as described above. Fig. 6(a) shows a PhC design with a 2×1 array of defects which resulted in evanescent in-phase coherent coupling. The PhC lattice constant, *a*, is 4.0 μm and the hole-diameter-to-lattice-constant ratio, *b/a*, is 0.70. The air hole located in the coupling region between the two defects has a reduced hole-diameter-to-lattice-constant ratio, *b'/a*, of 0.55. The holes in the PhC pattern were etched down approximately 19 periods, while the coupling region hole for this device was etched approximately 2 periods less due to plasma loading effects. Fig. 6(b) shows the near field image of the device with two PhC defect cavities operating at room temperature continuous wave (CW) at an injection current of 18.1 mA. Single mode operation (>30 dB) is observed from threshold to beyond the maximum power condition.
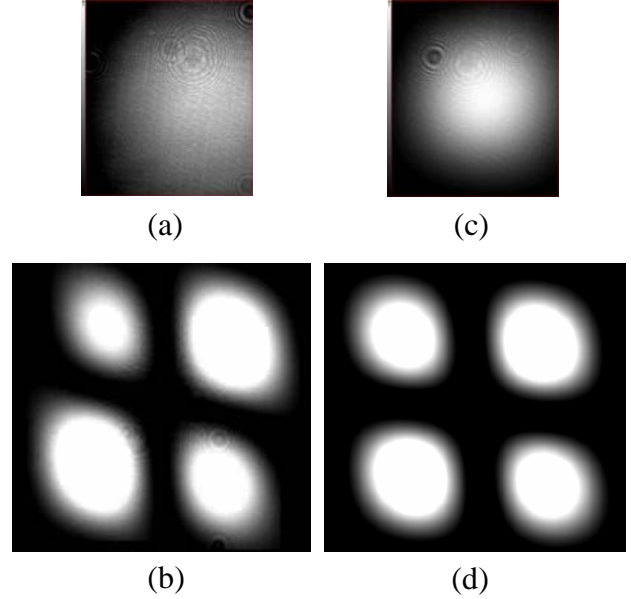
Fig. 7 illustrates the in-phase coherent coupling, measured at an injection current of 18.1 mA. Fig. 7(a) is the measured far field intensity contour plot and Fig. 7(b) provides the same data as a height coded intensity plot. A central on-axis lobe is observed with two subsidiary side lobes. Distinct nulls are observed between the lobes, indicative of a high degree of coherence between the two cavities and relatively equal lasing intensity in the two cavities [11]. The near field mode size is elliptical with major and minor axes of approximately 3.8 and 3.5 µm, respectively. These factors were

Figure 6. (a) PhC pattern with a 2×1 array of defect cavities. The hole located in the coupling region has a hole diameter of 2.2 µm. (b) Near field image of the fabricated PhC VCSEL operating in-phase coherently coupled.

included into a beam propagation method simulation, and the calculated results are shown as Figs. 7(c) and (d), respectively, showing the measured and calculated far field plots to be in good agreement.

A PhC design with a 2×2 array of defects also produces in-phase coherent coupling. The PhC lattice constant is 4.0 µm and the hole-diameter-to-lattice-constant ratio is 0.6. The two coupling region air holes located at the top and bottom of the coupling region have a reduced hole-diameter-to-lattice-constant ratio of 0.45, while the two coupling regions holes located at the left and right of the coupling region have a reduced hole-diameter-to-lattice-constant ratio of 0.30. The near field shows an additional optical intensity lobe located in the area at the center between the four coupling region holes. This device exhibited an in-phase coupled far field pattern from threshold to the maximum power condition (1.6 mW). A single dominant spectral peak (not shown) is observed over this operating range.
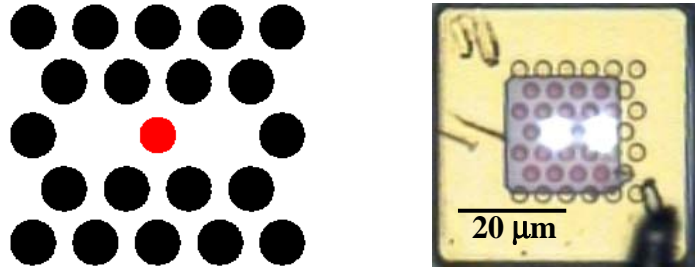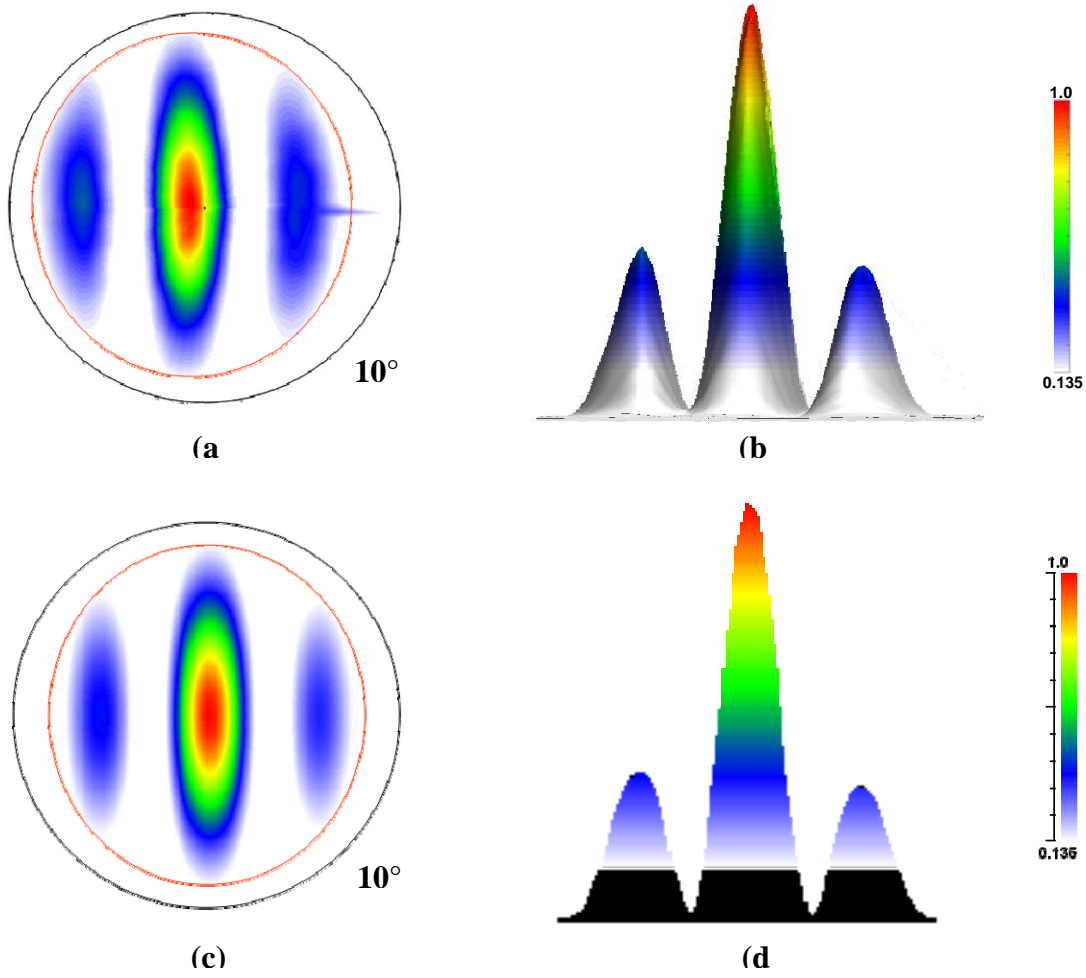
FIG. 7 (a) Measured far field intensity contour plot and (b) height coded intensity plot for the device of Fig. 6(b) showing in-phase operation. (c) Calculated far field intensity and (d) height coded intensity plot.

In summary, evanescent in-phase coherent coupling in 2×1 and 2×2 arrays of defect cavities in PhC VCSELs is reported. Far field measurements were presented to demonstrate the in-phase results and agreement between the measured and simulated in-phase far fields is shown. Modification of the effective refractive index and optical loss in the coupling regions between the defect cavities is the proposed mechanism which enables evanescent in-phase coherent coupling.

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