Electronically Controlled Two-Dimensional Steering of In-Phase Coherently Coupled Vertical-Cavity Laser Arrays

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***Abstract*—Photonic crystal vertical-cavity surface-emitting laser arrays can be designed to lase only in the in-phase array supermode. By electronically addressing the array elements independently, the relative phases between the emission from each element can be altered. The shift in relative phase results in the angular deflection of the central peak of the in-phase array supermode. We demonstrate highly controllable steering of a coherent laser beam produced by a 2 × 2 array of emitters.**

***Index Terms*—Optical coupling, semiconductor laser arrays, surface-emitting lasers.**

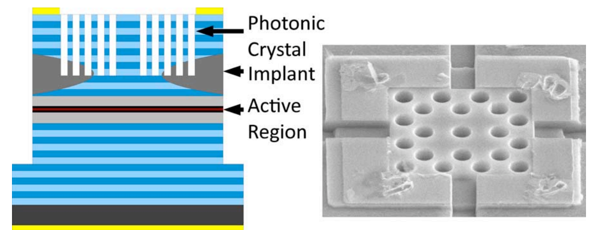

Fig. 1. Cross section and scanning electron micrograph of photonic crystal VCSEL array with separated contacts.

I. Introduction

VERTICAL-CAVITY surface-emitting laser (VCSEL) two-dimensional (2-D) arrays are useful for a variety of applications because of their low cost and ease of fabrication, and several approaches previously have been pursued to create coherently coupled VCSEL arrays [1]–[9]. VCSEL array structures have demonstrated beam steering capabilities, but these approaches often exhibit discontinuous steering, incoherent fields, or complicated and unreliable mechanical parts [10]–[13]. An alternative electronic steering method utilizes phase tuning via separate electrical injection to the array elements [14]. This approach is an optical analog of a phased array radio-frequency beam steering source [15], and it has the potential benefits of system robustness, radiation hardening, reduced steering time, greatly reduced system weight and size, and relatively low operation power. Recently, in-phase [16] and steerable ion-implanted VCSEL arrays [17] have been demonstrated, but unstable mode control causes the array output to become incoherent and the steering to be unpredictable at higher injection currents. In this work, we report single-mode in-phase 2 × 2 photonic crystal VCSEL arrays and demonstrate electronic beam steering in two dimensions that is predictable and controllable.

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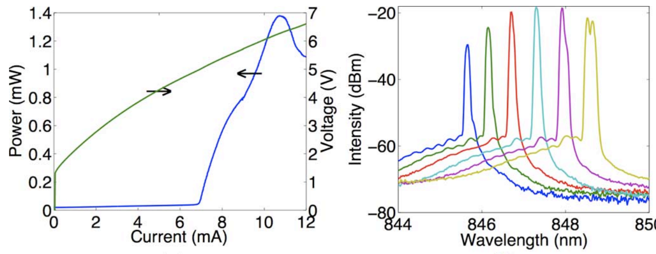
II. Design

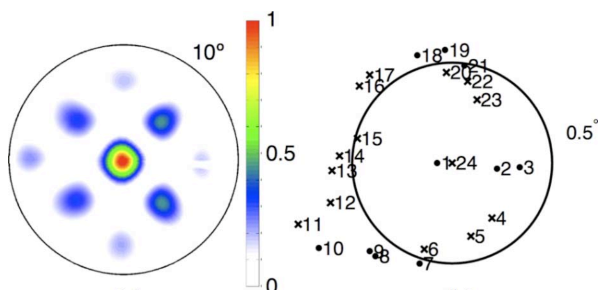
The 2-D VCSEL arrays reported here are similar to those described in [18]. There are 27 p-type top distributed Bragg reflector periods and 35 n-type bottom DBR periods on an n-type GaAs substrate. Between the top and bottom mirrors are three GaAs quantum wells that emit nominally at 850 nm. Backside metal is deposited on the substrate, and patterned metal ring contacts are deposited on the top surface. An inductively-coupled plasma reactive-ion etch (ICP-RIE) is used to etch the photonic crystal patterns (defined by optical lithography), where the average depth of the photonic crystal holes is approximately 75% through the top mirror. The gain apertures of the array are patterned and defined by proton implantation. After the aperture implantation, a separate multiple-implantation of protons is used for electrical isolation between different arrays. Finally, a focused ion beam (FIB) etch is used to electrically isolate the top contacts to allow for separate current injection to the array elements. A cross-sectional sketch and a scanning electron micrograph (SEM) of the 2-D VCSEL array are shown in Fig. 1.

The photonic crystal hole pattern provides stable index guiding around the array and helps to ensure only one supermode lases [19], [20]. For reference, a light-current-voltage characteristic and spectra of a similar single-contact array (i.e., no FIB etch of the top contact) is shown in Fig. 2. The approximately 7 mA threshold current is typical for the 2 × 2 arrays tested. Moreover, the lasers are typically single-mode near and above threshold, in the range where they are biased under steering conditions. By combining a photonic crystal with an implant-defined structure, we are able to realize stable in-phase operation of the array [18]. The photonic crystal is a square lattice (period $=$ 5.5 or 6 μm) of circular holes (diameter $=$ 0.6 or 0.7 times period). The defects in the lattice that define the array elements are chosen such that there is not an etched hole directly between any two elements. The implant



(a) (b)

Fig. 2. (a) The LIV characteristic and (b) the spectra from 7.1 to 12.1 mA of a single-contact 2×2 coherent VCSEL array.



(a) (b)

Fig. 3. (a) The in-phase far-field linear intensity pattern emitted by a 2×2 photonic crystal VCSEL array. (b) The angular locations of the far-field maximum for different current injections as described in Table I. The dots indicate that the current is varied between the left/right contacts, and crosses indicate the result when the top/bottom currents change. The circle represents 0.5° from the surface normal.

apertures are defined to be of the same size at the photonic crystal defects. Additionally, the holes nearest the aperture elements are reduced in size to as small as 0.3 times the photonic crystal period. These measures enable strong coupling between the lasers, as well as reduce the interelement loss to favor the in-phase array supermode [20]. The coherent in-phase far-field intensity pattern of a 2×2 photonic crystal VCSEL array is shown in Fig. 3(a).

III. Results

In general, the peak of the far-field radiation pattern is not necessarily directly on-axis. This appears to be a result of fabrication imperfections that cause the current injected into the array elements to be nonuniform. By independently adjusting the current injected into the four laser elements in a separated-contact device (such as in Fig. 1), the location of the central peak can be varied, as is expected when relative phase tuning between the elements of the coupled array occurs [14]. The far-field in Fig. 3(a) results from adjusting the relative injection currents above threshold to the four separate contacts so the central peak lies along the optical axis. The values of current to each contact are: top = 1.9 mA, bottom = 2.3 mA, right = 2.6 mA, left = 2.1 mA.

The changes made in the current injected into the four contacts (percent difference from the baseline values given for on-axis far-field) are shown in Table I. In each row of Table I, we change only one current level; the bold entry for each combination is the current that changes from the previous setting with a maximum variation of 10.5%. The angular location

TABLE I
Percent Change of Current From Baseline Values

Pt	Top	Bot	Rht	Lft	Pt	Top	Bot	Rht	Lft
1	0	0	0	0	13	5.3	**4.3**	-7.7	0
2	0	0	0	**-4.8**	14	**0**	4.3	-7.7	0
3	0	0	**3.8**	-4.8	15	0	**8.7**	-7.7	0
4	**5.3**	0	3.8	-4.8	16	**-5.3**	8.7	-7.7	0
5	5.3	**-4.3**	3.8	-4.8	17	**-10.5**	8.7	-7.7	0
6	**10.5**	-4.3	3.8	-4.8	18	-10.5	8.7	**-3.8**	0
7	10.5	-4.3	**0**	-4.8	19	-10.5	8.7	**0**	0
8	10.5	-4.3	0	**0**	20	-10.5	**4.3**	0	0
9	10.5	-4.3	**-3.8**	0	21	-10.5	4.3	**3.8**	0
10	10.5	-4.3	**-7.7**	0	22	-10.5	**0**	3.8	0
11	10.5	**0**	-7.7	0	23	**-5.3**	0	3.8	0
12	**5.3**	0	-7.7	0	24	**0**	0	3.8	0

that the central lobe of the in-phase mode steers to for each combination in Table I is mapped in Fig. 3(b). It is apparent from Fig. 3(b) that the steering angle of the peak of emission changes as the current to the different contacts is altered. It is also evident that this is well controlled steering, as changes in current to the left/right contacts deflect the beam left/right and changes to the top/bottom contacts steer the beam up/down. The 2×2 VCSEL array studied here is capable of steering the beam in two dimensions over a full angle of approximately 1°. For reference, the approximate full-width at half-maximum of the far-field is between 2.5° and 3° for all injection currents [18]. Thus, narrow-aperture detectors should be capable of detecting a change in intensity from steering on and off target. An increased maximum steering angle is expected by increasing the electrical isolation between the contacts and decreasing the separation between the array elements. Although this is a smaller steering range than previously reported [17], this steering occurs for the in-phase mode, and thus the emitted field is highly coherent and the beam deflection is predictable and controllable.

For practical beam steering applications, it is important that the central peak maintain its high visibility (and thus narrow angular beam profile) and high power. Fig. 4 demonstrates that the visibility (measured using the contrast of the maximum and minimum intensities in the far-field pattern [21]) is typically very high along all directions of the radiation pattern, and only at a few points does it diminish. It has been shown in edge emitting lasers that the preferred lasing mode can be changed by selectively tuning the current injected into different array elements [22]. Thus, the reduction in visibility can be attributed to another array supermode turning on as it becomes excited by a more favorable gain distribution. However, this photonic crystal VCSEL array provides very good mode control and typically maintains single-mode operation. Additionally, Fig. 5 illustrates that the percentage of total power in the central lobe is relatively constant as the beam is steered. The power in the central lobe is 19–23% of the total, which corresponds to approximately 1.5 to 2 times as much power as in any of the subsidiary lobes of the supermode. The small decrease in the central lobe power with increasing steering angle can be attributed to the central peak deviating from on-axis and thus power becomes redistributed

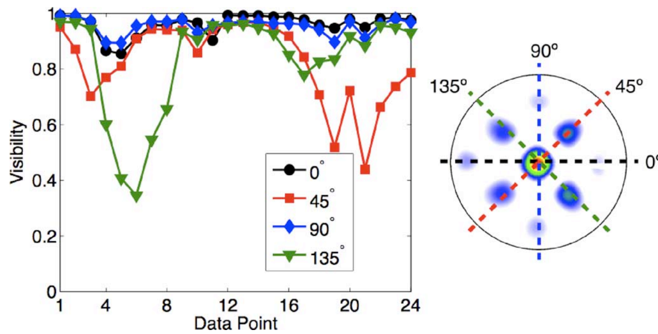


Fig. 4. Measured visibility along four directions (see inset) for the steering points specified in Fig. 3(b) and described in Table I.

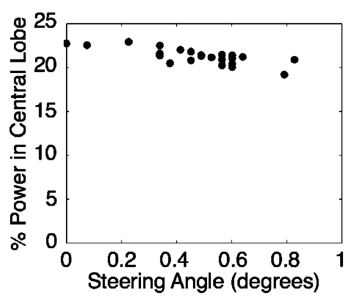


Fig. 5. Percent of the total output power in the central far-field lobe as a function of the steering angle deflected from on-axis.

from that lobe to subsidiary lobes that move closer to on-axis. In analogy with phased antennas, this power redistribution is a result of shifting of the peaks in the far-field envelope. Overall, the array maintains a stable, narrow-divergence beam that is desirable for steering applications.

IV. Conclusion

We have demonstrated the first realization of electronic beam steering in a VCSEL array utilizing only the in-phase array mode. Since only the in-phase mode is used, the steering is highly coherent and controllable. Moreover, unlike other beam steering approaches, this work exhibits continuous electronic steering achieved without moving parts or complicated fabrication steps. In order to increase the controllability and steering extent, better electrical isolation between array elements and different array geometries can be investigated. Larger arrays also could potentially allow for increased output power and smaller beam divergence, thus further increasing the detectable intensity contrast when steering.

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References

[1] H. J. Yoo, A. Scherer, J. P. Harbison, L. T. Florez, E. G. Paek, B. P. van der Gaag, J. R. Hayes, A. von Lehmen, E. Kapon, and Y. S. Kwon, "Fabrication of a two-dimensional phased array of vertical-cavity surface-emitting lasers," *Appl. Phys. Lett.*, vol. 56, no. 13, pp. 1198–1200, 1990.

[2] M. Orenstein, E. Kapon, N. G. Stoffel, J. P. Harbison, L. T. Florez, and J. Wullert, "Two-dimensional phase locked arrays of vertical-cavity semiconductor lasers by mirror reflectivity modulation," *Appl. Phys. Lett.*, vol. 58, no. 8, pp. 804–806, 1991.

[3] R. A. Morgan, K. Kojima, T. Mullally, G. D. Guth, M. W. Focht, R. E. Leibenguth, and M. Asom, "High-power coherently coupled 8 × 8 vertical cavity surface emitting laser array," *Appl. Phys. Lett.*, vol. 61, no. 10, pp. 1160–1162, 1992.

[4] M. E. Warren, P. L. Gourley, G. R. Hadley, G. A. Vawter, T. M. Brennan, B. E. Hammons, and K. L. Lear, "On-axis far-field emission from two-dimensional phase-locked vertical cavity surface-emitting laser arrays with an integrated phase-corrector," *Appl. Phys. Lett.*, vol. 61, no. 13, pp. 1484–1486, 1992.

[5] D. K. Serkland, K. D. Choquette, G. R. Hadley, K. M. Geib, and A. A. Allerman, "Two-element phased array of antiguided vertical-cavity lasers," *Appl. Phys. Lett.*, vol. 75, no. 24, pp. 3754–3756, 1999.

[6] F. Monti di Sopra, M. Brunner, H. P. Gauggel, H. P. Zappe, M. Moser, R. Hövel, and E. Kapon, "Continuous-wave operation of phase-coupled vertical-cavity surface-emitting laser arrays," *Appl. Phys. Lett.*, vol. 77, no. 15, pp. 2283–2285, 2000.

[7] D. Zhou and L. J. Mawst, "Two-dimensional phase-locked antiguided vertical-cavity surface-emitting laser arrays," *Appl. Phys. Lett.*, vol. 77, no. 15, pp. 2307–2309, 2000.

[8] L. Bao, N. H. Kim, L. J. Mawst, N. N. Elkin, V. N. Troshchieva, D. V. Vysotsky, and A. P. Napartovich, "Near-diffraction-limited coherent emission from large aperture antiguided vertical-cavity surface-emitting laser arrays," *Appl. Phys. Lett.*, vol. 84, no. 3, pp. 320–322, 2004.

[9] A. J. Danner, J. C. Lee, J. J. Raftery, Jr, N. Yokouchi, and K. D. Choquette, "Coupled-defect photonic crystal vertical cavity surface emitting lasers," *Electron. Lett.*, vol. 39, no. 18, pp. 1323–1324, 2003.

[10] T. Ide, M. Shimizu, S. Mukai, M. Ogura, T. Kikuchi, Y. Suzuki, R. Kaji, H. Itoh, M. Watanabe, H. Yajima, and T. Yemoto, "Continuous output beam steering in vertical-cavity surface-emitting lasers with two p-type electrodes by controlling injection current profile," *Jpn. J. Appl. Phys.*, vol. 38, no. 4A, p. 1966, 1999.

[11] M. I. Cohen, A. A. Allerman, K. D. Choquette, and C. Jagadish, "Electrically steerable lasers using wide-aperture VCSELs," *IEEE Photon. Technol. Lett.*, vol. 13, no. 6, pp. 544–546, Jun. 2001.

[12] A. Tuantranont, V. M. Bright, J. Zhang, W. Zhang, J. A. Neff, and Y. C. Lee, "Optical beam steering using mems-controllable microlens array," *Sens. Actuators A, Phys.*, vol. 91, no. 3, pp. 363–372, 2001.

[13] L. D. A. Lundeberg and E. Kapon, "Mode switching and beam steering in photonic crystal heterostructures implemented with vertical-cavity surface-emitting lasers," *Appl. Phys. Lett.*, vol. 90, p. 241115, 2007.

[14] A. C. Lehman, J. J. Raftery, Jr, A. J. Danner, P. O. Leisher, and K. D. Choquette, "Relative phase tuning of coupled defects in photonic crystal vertical-cavity surface-emitting lasers," *Appl. Phys. Lett.*, vol. 88, p. 021102, 2006.

[15] W. L. Stutzman and G. A. Thiele, *Antenna Theory and Design*. Hoboken, NJ: Wiley, 1981.

[16] A. C. Lehman and K. D. Choquette, "One- and two-dimensional coherently coupled implant-defined vertical-cavity laser arrays," *IEEE Photon. Technol. Lett.*, vol. 19, no. 19, pp. 1421–1423, Oct. 1, 2007.

[17] A. C. Lehman, D. F. Siriani, and K. D. Choquette, "Two-dimensional electronic beam-steering with implant-defined coherent vcsel arrays," *Electron. Lett.*, vol. 43, no. 22, 2007, DOI: 10.1049/el:20071762.

[18] D. F. Siriani and K. D. Choquette, "In-phase, coherent photonic crystal vertical-cavity surface-emitting laser arrays with low divergence," *Electron. Lett.*, vol. 46, no. 10, pp. 712–714, 2010.

[19] J. J. Raftery, Jr, A. J. Danner, J. C. Lee, and K. D. Choquette, "Coherent coupling of two-dimensional arrays of defect cavities in photonic crystal vertical cavity surface-emitting lasers," *Appl. Phys. Lett.*, vol. 86, no. 20, p. 201104, 2005.

[20] J. J. Raftery, Jr, A. C. Lehman, A. J. Danner, P. O. Leisher, A. V. Giannopoulos, and K. D. Choquette, "In-phase evanescent coupling of two-dimensional arrays of defect cavities in photonic crystal vertical cavity surface emitting lasers," *Appl. Phys. Lett.*, vol. 89, no. 8, p. 081119, 2006.

[21] A. C. Lehman, J. J. Raftery, P. S. Carney, and K. D. Choquette, "Coherence of photonic crystal vertical-cavity surface-emitting laser arrays," *IEEE J. Quantum Electron.*, vol. 43, no. 1, pp. 25–30, Jan. 2007.

[22] E. Kapon, Z. Rav-Noy, L. T. Lu, M. Yi, S. Margalit, and A. Yariv, "Phase-locking characteristics of coupled ridge-waveguide inp/ingaasp diode lasers," *Appl. Phys. Lett.*, vol. 45, p. 1159, 1984.