Coherence of Photonic Crystal Vertical-Cavity Surface-Emitting Laser Arrays

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***Abstract*—We measure and compare the coherence properties of 2×1 arrays of photonic crystal vertical-cavity surface-emitting lasers. Antenna array theory applied to the measured far field intensity patterns is used to determine the phase of the complex degree of coherence, which is found to vary with current injection. The amplitude of the complex degree of coherence is determined by calculating the visibility from the far field patterns and making near field measurements of the relative intensities between lasing defects. We find that the amplitude and phase of the complex degree of coherence are correlated, such that coherence is maximized near in-phase and out-of-phase coupling conditions, and controllable by independent current injection to each array element.**

***Index Terms*—Coherence, photonic crystal (PhC), vertical cavity surface-emitting laser (VCSEL).**

I. Introduction

COHERENTLY coupled arrays of vertical-cavity surface-emitting lasers (VCSELs) provide potential solutions for applications such as optical storage, optical imaging, and beamsteering. Evanescent optical coupling between two-dimensional array elements of VCSELs has been studied extensively [1]–[10]. One of the major disadvantages with this coupling approach is that large inherent loss between cavities typically causes the laser phases to lock together out-of-phase [2]. This condition corresponds to the emission from one cavity being 180 deg out-of-phase with emission from a neighboring cavity, resulting in a far-field profile with an on-axis null. For most applications, one would prefer that the coupled lasers emit with the same phase to produce an in-phase far field profile with an on-axis central lobe or have a variable phase difference which would produce electronic beam-steering. Antiguided VCSELs [11], [12] and phase-corrected arrays [6] have been developed as an alternative approach to achieve in-phase coupling, but these devices have complex fabrication processes and stringent design tolerances.

Arrays of two-dimensional photonic crystal (PhC) VCSELs may provide solutions for these limitations by defining separate cavities with reduced loss between regions to allow for both in-phase operation [13] and possible tuning of the relative phase [14]. Conventional VCSELs are transformed into PhC VCSELs by etching a periodic pattern of holes into the top facet [15]. The absence of a hole creates a defect which can define an area where lasing will occur. The holes lower the effective index and therefore confinement of photons in the defect can be accomplished. Multiple defects allow for multiple lasing regions in close proximity such that evanescent coupling between the defect cavities occurs [16].

In this paper, we show that the change in bias current to a 2×1 PhC VCSEL array alters the coherence of the light emitted, which is measured using the visibility of the far field combined with near field intensity profiles. As injection current is varied, examination of the far field pattern shows that the relative phase between the light emitted from each defect varies [14]. This change causes a shift in the angle(s) of peak far field emission. By comparing the magnitude of the complex degree of coherence versus relative phase between defects, we find the coherence is maximized near the in-phase and out-of-phase conditions, which has implications for the device operation.

II. Device Structure and Experiment

PhC VCSELs [15] are created when a periodic pattern of holes is etched into the surface of a VCSEL. Defects are formed by leaving out holes from the pattern, which produces a region of higher refractive index and thus lasing occurs within these regions. An example of a near field image from a PhC VCSEL array with two lasing defects is shown in Fig. 1(a). Fig. 1(b) is a schematic showing the cross-sectional view of a device with two defects as well as the effective refractive index within and around the defect regions. For the devices studied, oxide-confined VCSELs were first fabricated. Following the fabrication, a layer of SiO_2 was left on the top facet for a focused ion beam etch (FIBE) process step [17]. A pattern with a triangular lattice similar to that shown in the image in Fig. 1(a) was etched through the top layer of oxide and partially into the top mirror. The patterned oxide then was used as a mask to fully transfer the pattern into the top facet of the VCSELs during an inductively coupled plasma etch using $SiCl_4$ as the etching gas. The remaining top oxide was then removed with a freon process in a reactive ion etching system. After device testing, an additional FIBE was performed on some of the arrays. Parts of the metal contacts were removed using a FIBE as can be seen in Fig. 1(a).

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Color versions of Figs. 1 and 3–8 are available online at http://ieeexplore.ieee.org.

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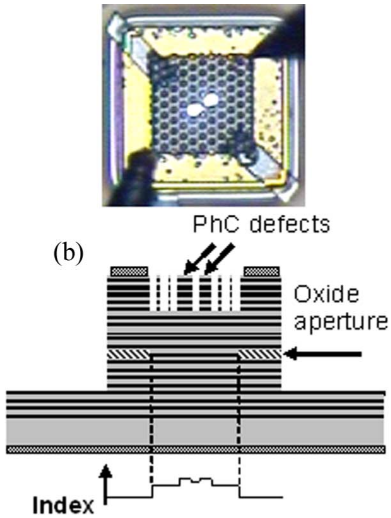

Fig. 1. (a) Top view of lasing PhC VCSEL 2 × 1 array with segmented electrical contacts. (b) Cross section schematic of PhC VCSEL.

TABLE I
SUMMARY OF PhC VCSEL 2 × 1 ARRAY PARAMETERS

Laser	# top mirror periods	Doping of top mirror	Phc etch depth (periods)	Diameter of pattern holes (μm)	Diameter of hole between defects (μm)	Separate contacts by FIBE
A	25	n	19	2.4	1.2	No
B	25	n	19	2.8	2.2	No
C	22	p	19	2.8	1.6	Yes
D	22	p	19	2.8	1.6	Yes

In addition, a thin line was also etched through the top layer of the facet which is highly doped and therefore highly conductive. This line is positioned between the defects and extends to the metal contact ring. Although the defects are not completely electrically isolated, it is possible to preferentially inject current to each.

Four devices are considered which each have a 2 × 1 array of defects in a triangular lattice of holes with a pitch of 4 μm. The PhC dimensions were chosen to create single-mode operation in the case of a single defect [18], and the key parameters for these lasers are summarized in Table I. Each device has 34 or 35 bottom distributed Bragg reflector (DBR) periods with 22 or 25 top DBR periods, respectively. As shown in the table, the hole between the defects has been reduced in diameter to promote optical coupling [16]. All of the lasers emit nominally at 850 nm. The epitaxial differences as well as the small differences in the PhC structures between these devices do not significantly influence the coherence behavior described in the next section.

Both near-field and far-field measurements were made using a Keithley current source or an Agilent pulse-generator to drive the lasers. The near field intensities were measured by monitoring the output of the attenuated camera image on an oscilloscope. A goniometric radiometer was used to measure the interference pattern in the far field.

III. Phase and Coherence Properties

A. Relative Phase Between Defects

As discussed in [14], the relative phase between the two coupled cavities may be determined from the far field pattern. This quantity is also known as the phase of the complex degree of coherence as presented in [19]. Using basic antenna array theory, the beam pattern may be separated into the individual element pattern times the array factor. The array factor would be the resultant beam pattern in the event of isotropic point sources. From [20] the array factor is given by the form

$$|ARFAC(\psi)| = \left|\frac{\sin(N\psi/2)}{\sin(\psi/2)}\right| \tag{1}$$

where N is the number of elements in the array. ψ is given by

$$\psi = kd\cos\theta + \delta \tag{2}$$

where $k = 2\pi \mathrm{n}/\lambda$ is the wavevector, n is the index of refraction, λ is the emission wavelength in free space, d is the distance between emission centers, θ is the angle measured from parallel to the VCSEL facet along the axis containing the defects, and δ is the relative phase difference of the emission between adjacent elements. The array factor in (1) produces many grating lobes, but only lobes falling within the emission pattern of a single element will radiate. In our case, we use a Gaussian envelope to approximate the diffraction limited radiation from each defect. This envelope explains why even for a relatively large kd value of approximately 51 radians, we do not observe more than two main lobes. Because the Gaussian envelope is selecting out only the portion of the array factor near perpendicular to the VCSEL, changes in wavelength with current injection have a minimal effect on the beam pattern. When δ is zero (in-phase), a main on-axis lobe is emitted in the direction perpendicular to the surface of the VCSEL. As δ is varied away from zero, the angle of emission for that lobe moves away from perpendicular along the axis containing the line of array elements. The out-of-phase case ($\delta = 180$ deg) produces two nominally equal lobes with an on-axis null.

PhC VCSEL arrays were tested under continuous-wave (CW) and pulsed operation at room temperature. During operation, the near-field pattern of these devices indicates lasing in the two defect regions as in Fig. 1(a), and a single spectral peak is observed (not shown). One-dimensional scans of the far field profile along the array axis for a number of CW bias currents applied to Lasers A and B are shown in Fig. 2. As expected, perpendicular scans reveal only a Gaussian-like element pattern. Laser A varies around an out-of-phase condition, and Laser B varies around an in-phase condition. The difference between the nominal phase condition between Lasers A and B arises from the difference in the coupling region loss between lasing cavities of each sample. As the electrical bias to the VCSEL varies, the peaks in the far field patterns change in relative intensity and shift in angle. Between 25 and 60 mA, the right peak emission of Laser A rotates by 1.60 deg, and the left peak emission rotates by 1.37 deg. Over a range of 1 mA, the peak emission from Laser B rotates 2.6 deg in the far field. This shift in emission angle is consistent with a relative phase change between the two defect regions as explained by array theory.

Using the formulation given above with our measured far field data, it is possible to calculate the relative phase difference between array elements. The locations of the minima in the patterns were used to determine the phase difference. From the

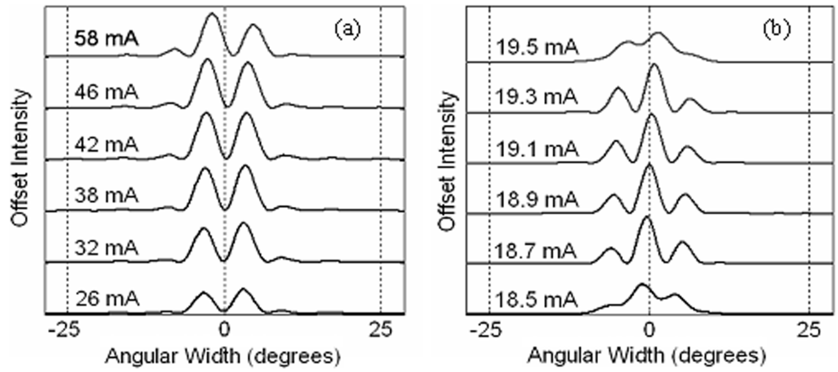

Fig. 2. Offset far field scans (intensity versus angle) along the array axis at injection currents as shown for (a) out-of-phase Laser A with an approximate threshold current of 24 mA and (b) in-phase Laser B with an approximate threshold current of 16 mA.

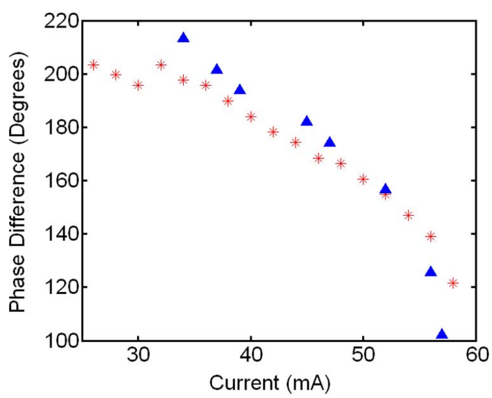

Fig. 3. Relative phase difference between cavities of Laser A at various CW ($*$) and pulsed (▲) injection current.

theory, we have determined that the difference in the relative amplitude between defects will affect the magnitude of the minima but not the location of the minima with respect to phase. This allows us to assume equal amplitudes for each element in our simulations, which is consistent with visibility measurements discussed later. A plot of the phase difference as measured by the far field profile between the defects is shown in Fig. 3 for Laser A. As the dc current varied from 34 to 58 mA, the phase difference between the defects varied from 203 to 122 deg. In order to achieve a larger angular shift in the far field patterns from this variance in phase, one would need to reduce kd by either increasing the wavelength or decreasing the distance between emission centers.

The relative changes in phase could be caused by thermal or electronic effects on the refractive index in the optical path of each element. In order to examine the effects of heating, far field measurements were made under pulsed injection conditions. The phase tuning effect under pulsed operation (1 μs period, 50% duty cycle) is nearly identical to that observed under continuous wave operation and is also plotted in Fig. 3. Although the pulse duration used may not completely eliminate thermal effects, it suggests that thermal effects are not a main contributor to this behavior because the phase tuning did not decrease. Another contribution to the refractive index in the VCSEL cavities arises from the injected electrons. Thus the suppression of the refractive index in the lasing regions as carrier density increases along with a varying current distribution between the cavities likely plays a role in how the cavities are phase-locked.

B. *Coherence Between Defects*

The far field patterns are examined to determine the degree of coherence between defects. As discussed by Mandel and Wolf for Young's two pinhole experiment [19], which is similar to a 2×1 array if each defect is considered as a pinhole, the visibility of an interference pattern may be found by the formula

$$V = \frac{\langle I\rangle_{\max} - \langle I\rangle_{\min}}{\langle I\rangle_{\max} + \langle I\rangle_{\min}} \tag{3}$$

where $\langle \mathrm{I}\rangle_{\max}$ is the averaged maximum intensity and $\langle \mathrm{I}\rangle_{\min}$ is the averaged minimum intensity in the interference pattern. For a stationary, ergodic field with two elements the visibility is related to the coherence by

$$V = \frac{2}{\sqrt{I_1/I_2} + \sqrt{I_2/I_1}}|\gamma| \tag{4}$$

where γ is the complex degree of coherence between adjacent devices and I_j is the near field intensity of the jth element. The complex degree of coherence is a measure of how correlated fluctuations in the field emitted from one defect are with the fluctuations in the field emitted from the other defect. Therefore, the magnitude of the complex degree of coherence between two defects in a PhC may be found from the visibility of the far field patterns as well as near field measurements of the relative intensities between defects. The 2×1 arrays are similar but not completely equivalent to Young's two-pinhole experiment. The only significant radiation occurs in the defect regions which we consider as the "pinholes," so the lasers are adding Gaussian-like element patterns, which must be de-convolved in order to get an accurate measurement of the visibility. Because a Gaussian beam is maximum on axis, values near theta equals 0 deg are used for the calculation described below.

The visibility and the complex degree of coherence are calculated and plotted as a function of current as shown in Fig. 4 for Laser C, where current is injected equally into both of the segmented contacts. In Fig. 4, it is clear that the visibility

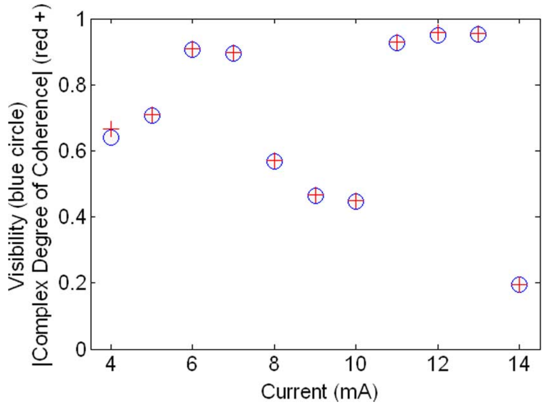

Fig. 4. Visibility (o) and coherence (+) as a function of dc injection current for Laser C with threshold current of 3.5 mA.

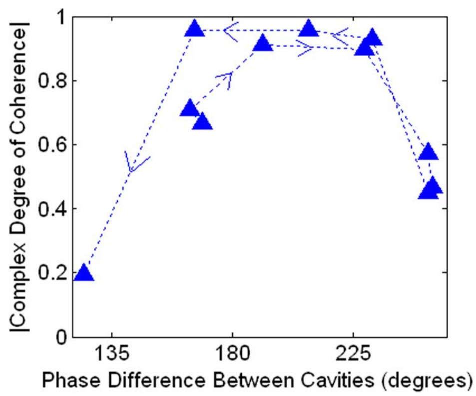

Fig. 5. Coherence as a function of relative phase between cavities for Laser C. The points follow the arrows along the dotted line as injection current is increased.

does not significantly differ from the coherence magnitude. Thus the factor to correct for differences in near-field intensities has little effect for the range of intensities measured, as expected from uniform current injection into both defects. The coherence versus relative phase between elements is plotted in Fig. 5. From this plot it is clear that as the current is increased (along the dotted line in the direction of the arrows) the relative phase between adjacent defects also changes, and the coherence changes with the phase. When the phase is near 180 deg, the coherence nears unity. As the phase moves away from out-of-phase coupling, the coherence decreases. Behavior similar to this was seen in other out-of-phase coupled devices as the relative phase varied around 180 deg with injection current. The visibility versus phase of Laser B, which exhibits varying phase around an in-phase condition, is shown in Fig. 6. In this case the coherence is peaked around the in-phase condition.

The magnitude of the degree of coherence provides information about how correlated the field emitted from one defect is to the field emitted from the other defect. To explain the behavior shown in Figs. 5 and 6, we consider the longitudinal field of the VCSEL. Previous work [1], [2] predicts that evanescently coupled elements will lock in-phase or out-of-phase. Since the VCSEL longitudinal mode is peaked in the active region, it is consistent that this coupling occurs primarily there. As the optical fields propagate into the mirrors, their longitudinal magnitudes decrease dramatically. Thus their transverse overlap and coupling should also decrease. If the two fields experience the

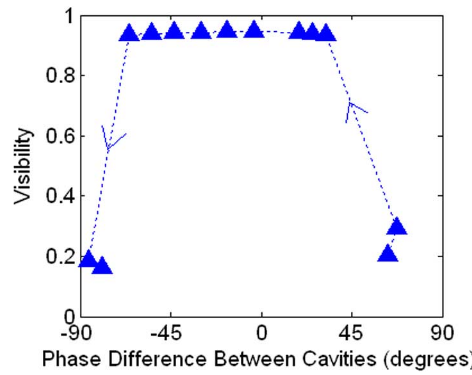

Fig. 6. Coherence as a function of relative phase between cavities for Laser B. The points follow the arrows along the dotted line as injection current is increased.

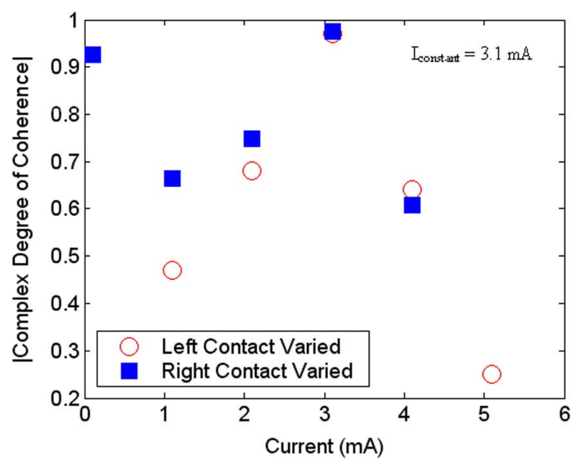

Fig. 7. Degree of coherence as current to one contact is changed while the other is fixed at 3.1 mA for Laser D which has a segmented top contact. With equal current to each contact, the threshold current is 4 mA.

identical path propagating away from the active region, one would expect the fields to be highly correlated at the top facet, and the phase relationship from the active region would be maintained. If the mirror under one defect exhibits more optical loss, a different temperature, or a different carrier induced index, one would expect that the fields at the surface of the VCSEL would be less correlated and that the phase between the two defects may vary from what it was in the active region.

To explore this hypothesis we examine the PhC VCSELs in which we have separate current injection into each defect cavity. Figs. 7 and 8 show the results for Laser D when the right and left current injections are controlled separately. The coherence versus current is shown in Fig. 7. For both sets of points in Fig. 7, the coherence is low when the current injected to the variable contact is 1.1 mA and increases until the injection current to both contacts is 3.1 mA. As current to the variable contact continues to increase above 3.1 mA, the coherence decreases. Note that if the contact with constant current were held at 4.1 mA, the maximum coherence would be reached when injection current to the variable contact approached 4.1 mA. Thus, there is maximum coherence when both contacts are injected with equal current. Coherence versus relative phase between elements when the current to one contact is held at 3.1 mA, and the current to

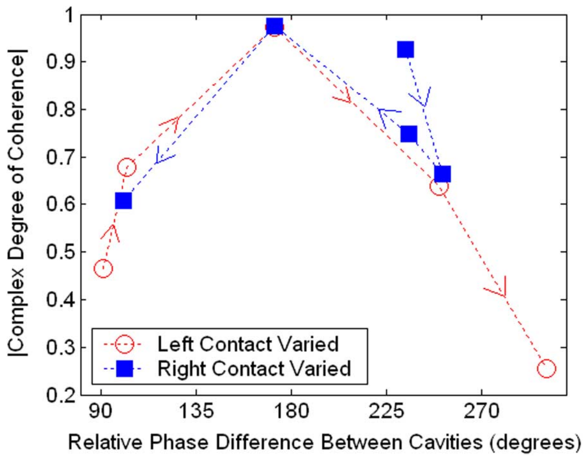

Fig. 8. Changes in coherence with relative phase for Laser D. The points follow the arrows along the dotted line as injection current to one contact is increased.

the other contact is varied are shown in Fig. 8. As current to one contact is varied, the coherence follows in the direction of the arrows along the dotted line between data points in Fig. 8. As would be expected, increasing current in the right contact produces an opposite phase shift as increasing current to the left contact. The elements have the highest degree of coherence around an out-of-phase condition. The bias conditions showing high coherence represent equal current injection to both contacts. Figs. 7 and 8 show that symmetrical current injection produces the highest coherence, while asymmetrical injection, which can create a differing relative phase, produces lower coherence.

IV. Conclusion

We have studied the coherence properties of 2 × 1 arrays of PhC VCSELs. By measuring the far-field and near-field intensity patterns, we have found that the relative phase between fields emitted from each defect as well as the magnitude of the complex degree of coherence vary with current injection. By varying the injection into each cavity, the phase difference can be changed, producing beam steering. Our results also show that coherence varies with the relative phase angle and is maximized near a purely in-phase or out-of-phase condition. Our explanation of this result is that the lasing fields under each defect are locking in-phase or out-of-phase within the active region. Because of differences in the optical path through the top mirror, the phase and coherence varies at the top facet where are measurements are made. This explanation is consistent with our experiments where the current to each defect is controlled by a separate contact. The ability to electronically tune both coherence and phase has implications for beam-steering applications.

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