Relative phase tuning of coupled defects in photonic crystal vertical-cavity surface-emitting lasers

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Evanescent coupling can be achieved by patterning the top facet of a vertical-cavity surface-emitting laser (VCSEL) with a multiple defect photonic crystal pattern. We show that for 2×1 coupled defect arrays, the phase between these emission sites changes as the current is varied. The phase variation is manifest in the far field pattern and may be determined using antenna array theory. It is found that the phase varies 81 deg between transversely coupled cavities as the current to the VCSEL is varied by 24 mA. This corresponds to a far field angular change of approximately 1.5 deg. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2164347]

Evanescent optical coupling between array elements of vertical-cavity surface-emitting lasers (VCSELs) has been studied extensively.[1–8] One of the major disadvantages with this approach is that the large inherent loss between cavities typically causes the laser phases to lock together out-of-phase.[3] That is to say, the emission from one cavity is 180 deg out-of-phase with emission from a neighboring cavity. 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 controllable variable phase difference which would produce electronic beam-steering. Antiguided VCSELs[9,10] and phase-adjusted arrays[5] have been studied as an alternative approach to achieve in-phase coupling, but these devices are more complicated to fabricate and have stringent design tolerances.

We have previously demonstrated that two-dimensional (2D) photonic crystals (PhC) with multiple defects may be patterned on the top facet of a VCSEL to create a coherent array.[11,12] It was initially found that a PhC VCSEL would create an incoherent or out-of-phase far-field pattern depending on the photonic crystal geometry. In the present work, however, we show that for optically coupled arrays, the relative phase difference between lasing defects is not constant with changing bias to the VCSEL. A similar technique was used for varying the phase between injection locked VCSELs.[13]

In order to examine the coupling of multiple defects in a PhC VCSEL, 2D patterns of air holes were defined on the surface of nominally 850 nm VCSELs using electron beam lithography.[14] After the holes were patterned, an inductively coupled plasma reactive ion etch using $SiCl_4$ as the etching gas transferred the pattern into the top facet of the VCSELs. The patterns consisted of triangular lattices with two holes absent as seen in Fig. 1(a). The VCSELs studied are 50 μm in diameter and have 25 top and 35 bottom distributed Bragg reflector (DBR) periods of alternating quarter-wave $Al_{0.92}Ga_{0.08}As/Al_{0.16}Ga_{0.84}As$ layers. The PhC etch depth was nominally 19 periods of the top DBR. Lateral electrical confinement is provided by an oxide aperture.

The 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. 2D scans of the far field profile for a number of cw bias currents are shown in Fig. 2(a). 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 is moved by 1.60 deg, and the left peak emission is moved by 1.37 deg. This shift in emission angle is characteristic of a relative phase change between the two defect regions as explained by array theory.

To describe the emission from two defect regions, we may use an established antenna theory for linear equally spaced arrays[15] and then consider the two defects in the photonic crystal as two array elements. According to this formulation, an array factor term may be multiplied by the field emission from an individual element to give the total far field pattern from multiple elements. This array factor is given by

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

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

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

where $k=2\pi n/\lambda$ 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 along the x axis to perpendicular to the VCSEL facet,

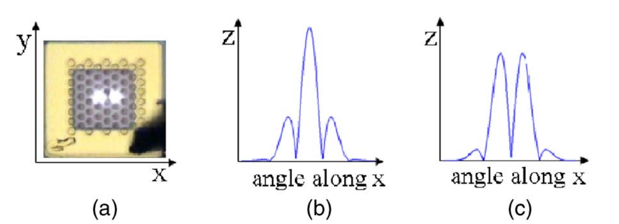

FIG. 1. (a) Example of 2×1 photonic crystal defect pattern. (b) Plot of far field beam pattern for in-phase emission. (c) Plot of far field beam pattern for out-of-phase emission.

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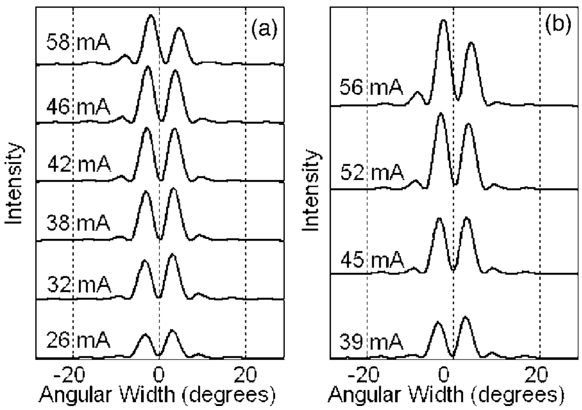

FIG. 2. (a) Offset far field scans at 26, 32, 38, 42, 46, and 58 mA. (b) Offset far field scans for pulsed operation (1 μs period, 50% duty cycle) with current values of 39, 45, 52, and 56 mA.

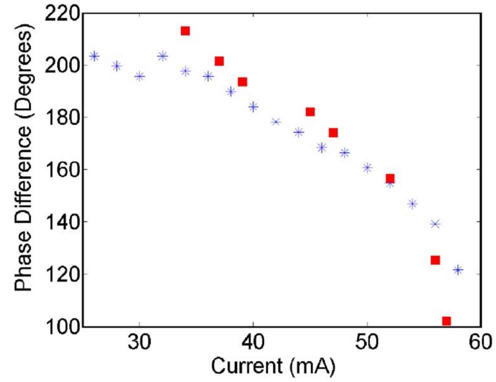

FIG. 3. Relative phase difference between cavities at various cw (*) and pulsed (■) biases.

and δ is the relative phase difference between adjacent emitters. When δ is zero (in-phase), a main on-axis lobe is emitted in the direction perpendicular to the surface of the VCSEL as shown in Fig. 1(b). As δ is varied away from zero, the angle of emission for that lobe sweeps away from perpendicular along the axis containing the line of array elements. The out-of-phase case ($\delta = 180$ deg) is shown in Fig. 1(c) which would produce two nominally equal lobes with an on-axis null. Also, it is important to remember that 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.

Using this formulation along 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 with the calculation described above to determine the phase difference. From the theory, we have determined that the relative amplitude between defects will affect the magnitude of the minima but not the location of the minima with respect to phase. For simplicity, in our simulations we assume equal amplitudes for each element. A plot of the phase difference between the cavities is shown in Fig. 3. 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 see a larger angular shift in the far field patterns from this variance in phase, one would need to reduce kd. This would require increasing the wavelength or decreasing the distance between emission centers.

The relative changes in phase may be related to thermal or electronic effects on the refractive index. In order to examine the effects of heating, far field measurements were made under pulsed conditions, as shown in Fig. 2(b). One can see from Fig. 2(b) that variations in the far field with respect to current still exist for pulses spaced by 1 μs and having a 50% duty cycle. The phase tuning effect under pulsed operation, also plotted in Fig. 3, is nearly identical to that observed under continuous wave operation. Although these pulses may not completely eliminate thermal effects, since the phase tuning did not decrease, it suggests that thermal effects are not a main contributor to this behavior. 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.

In conclusion, we have shown variation in the relative phase between two defects in a PhC VCSEL as the bias current is varied. Using antenna array theory, we can compute the numerical value of this phase difference and observe variations as large as 80 deg. The possibility to vary the phase with current holds promise for beam-steering applications. Moreover, it would be desirable to tune the relative phase difference between elements around the in-phase condition, as recently reported.[16]

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