Beam steering with optical phased arrays is accomplished by introducing a relative phase shift between array elements [1]. This is typically achieved by altering the refractive index difference between elements, which alters the optical path length of incident radiation traveling through the elements. Beam steering with VCSEL arrays has also been shown to rely on such a refractive index variation [2], which is implemented by adjusting the current injection to the elements. However, if we view the VCSEL array as a waveguide from the active region through the distributed Bragg Reflectors, it can be shown that the index-induced phase shift between elements would only account for less than 1/100th of the observed phase shift [2]. It is thus evident that phased VCSEL arrays rely on a fundamentally different phase-shifting mechanism. To investigate this, we turn to coupled mode theory, which has previously been applied to the dynamics of coupled edge emitting laser arrays and phase tuning in injection-locked VCSELs [3, 4].

The dynamic coupled mode equations for semiconductor laser arrays can be normalized to yield [3]

\[
\frac{dX_m(t)}{dt} = Z_m X_m - \kappa \tau_\phi \left[ X_m \sin(\phi_m - \phi_e + \psi) - X_{\text{th}} \sin(\phi_m - \phi_e + \psi) \right]
\]

\[
\frac{d\phi_m(t)}{dt} = \alpha Z_m - \kappa \tau_\phi \left[ \left( X_m / X_e \right) \cos(\phi_m - \phi_e + \psi) + \left( X_{\text{th}} / X_e \right) \cos(\phi_m - \phi_e + \psi) \right] + \left( \omega_{\text{native}} - \omega \right) \tau_\phi,
\]

where \( \kappa \) is the coupling strength between elements, \( \tau_\phi \) the photon lifetime, \( \Psi \) the constant coupling phase (0 for in-phase arrays, \( \pi \) for out-of-phase), \( \alpha = -5 \) the linewidth enhancement factor [5], \( \omega \) the angular frequency, \( X_m \) the normalized field amplitude, \( \phi_m \) the phase, and \( Z_m \) the normalized excess carrier density in the \( m \)th laser. For a two-element array where \( m = 1(2) \) for the left (right) element and \( X_1 = X_2 = 0 \), the phase shift between elements is found to correspond with the native cavity resonance of each element, \( \omega_{\text{m native}} \) per

\[
\omega_{1,\text{native}} = \omega_{2,\text{native}} = -\kappa X_1 X_2 \left[ \cos(\phi_1 - \phi_2 + \psi) + \alpha \left( \sin(\phi_1 - \phi_2 + \psi) \right) \right],
\]

\[
\Delta \omega = \Delta \omega_{\text{native}} = -\kappa \left[ \frac{X_1 + X_2}{X_1 X_2} \sin(\phi_1 - \phi_2 + \psi) + \left( \frac{X_1}{X_2} - \frac{X_2}{X_1} \right) \cos(\phi_1 - \phi_2 + \psi) \right],
\]

where \( \omega_{\text{m native}} \) is the angular frequency of the coupled emission.

Coherently coupled leaky mode VCSEL arrays with \( \Psi = \pi \) and \( \Psi = 3\pi / 2 \) are examined where the current injection into each element is varied [6]. The 2x1 arrays are coherently coupled together when the difference between their native resonance frequencies, \( \Delta \omega \), falls within a certain locking range which corresponds to a range of varying injection current. Outside of this range, the elements are assumed to operate independently at their native resonances, which must be further examined. The far field profiles of these arrays are shown at varying current differences between the elements in Fig. 1. The phase shift between elements at each current difference is extracted from fitting the propagated near field to the far field [7]. The field amplitudes \( X_1 \) and \( X_2 \) are determined as the square root of the maximum intensity measured in each element. As can be seen from the inset of Fig. 1(b), \( X_2 > X_1 \) for the \( \Psi = 3\pi / 2 \) array. In Fig. 2 we show the phase difference retrieved from experiment and the lasing emission wavelength. The coupling strength is approximated from Eqn. 4 as \( \kappa = -\Delta \omega_{\text{native}} / 2\alpha \), where \( \Delta \omega_{\text{native}} \) is the maximum detuning between resonant frequencies, outside of which spectral splitting is observed. This value is obtained from \( \Delta \lambda_{\text{native}} \) as shown in Fig.

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2(b) ($\Delta \lambda_{\text{lock}} = 0.17, 0.06$ nm for $\Psi = 0, 3\pi / 2$, respectively). Within the locking range, $\lambda_{\text{lock}}$ is obtained experimentally. The native resonance of both elements within this range can then be retrieved with Eqn. 3, as plotted in Fig. 2(b). A relatively linear variation of both cavity resonances is shown, while $\lambda_{\text{native}}^2$ varies to a greater extent with increased current to element 2. It is also noteworthy that for the $\Psi = 3\pi / 2$ array, $\lambda_{\text{lock}}$ is found to reside closer to $\lambda_{\text{native}}$ due to the disparity between $X_2$ and $X_1$. Based on dynamic coupled mode theory, the phase shifting mechanism in phased vertical cavity laser arrays is thus shown to depend on detuning between the resonant frequencies of the element cavities.

References


Fig. 1. Far field profiles of coupled arrays with (a) $\Psi = \pi$ and (b) $\Psi = 3\pi / 2$. Insets show near field intensity profiles used to obtain $X_1$ and $X_2$ for the arrays.

Fig. 2. (a) Phase retrieved from experiment for the two arrays with varying current injection into the elements. (b) Peak wavelengths measured (circles) and from Eqn. 3. The current and wavelength of the $\Psi = 3\pi / 2$ array are offset by +0.4 mA and +1.5 nm, respectively, for clarity.