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Volume 9, Number 5, October 2017

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DOI: 10.1109/JPHOT.2017.2750740
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DOI:10.1109/JPHOT.2017.2750740
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Abstract: We show that optical coupling can be achieved reproducibly and with high yield by resonance tuning the elements of substrate-emitting and top-emitting vertical-cavity surface-emitting laser arrays. The resonance tuning is enabled by electrical isolation of the lasing elements in the array, which in this paper is done by post-fabrication processing. Prior to electrical isolation, the laser arrays exhibit incoherent optical properties. Using resonance tuning, both in-phase and out-of-phase coherent modes are observed.

Index Terms: Coherent arrays, semiconductor laser arrays, vertical cavity surface emitting lasers

1. Introduction

Coupling between two or more oscillators occurs in numerous phenomena in photonics. The physical interactions between photonic oscillators gives rise to a diversity of properties that can be harnessed for various applications. An example is the optical coupling between semiconductor lasers, such as vertical cavity surface-emitting lasers (VCSELs) in 1-dimensional (1D) or 2-dimensional (2D) arrays [1]. Optically coherent VCSEL arrays can be created by defining multiple lasing apertures or elements in close proximity. Coherently coupled VCSEL arrays are of interest for high brightness operation. When multiple laser elements are coherently combined, the result is a narrow divergence radiation mode whose intensity grows with the square of the number of array elements. Both in-phase (intensity peak on axis) and out-of-phase (intensity node on axis) coherent modes can be observed.

There are several emerging and previously demonstrated coherent VCSEL applications. These include utilizing high brightness for pumping and high power [2], optical sensing and beam steering [3], along with using coupled arrays to increase the modulation bandwidth [4]. There have been several optically coupled VCSEL array structures previously demonstrated, but they often suffer from low yield of high coherence arrays. For example, coherent VCSEL arrays using close-pitch etched pillars [5], a checker-board pattern of phase shifting layers [6], cavity resonance modification
[7] or regrowth of high index material between the elements [8] to create anti-guiding, and patterned reflectivity [9] have all demonstrated optical coherence. However, these approaches often rely upon challenging fabrication strategies (such as epitaxial regrowth on AlGaAs surfaces) or stringent fabrication tolerance (such as nanometer accuracy of an anisotropic etch). Moreover the VCSEL array structures do not always provide in-phase coherent operation if they achieve coherence at all.

We have developed and demonstrated 2D photonic crystal ion implanted VCSEL arrays, in both top-emitting [10] and substrate-emitting [11] geometries, that exhibit leaky mode optical coupling between the elements. The etched photonic crystal pattern of holes provides a means of defining a preferred optical mode, while the aligned pattern of un-implanted regions defines the array elements were gain is introduced. The photonic crystal provides stable index guiding for array elements and greater optical loss for higher order modes [12]. Through proper design of the photonic crystal hole pattern, combined with the ion-implanted apertures, an array of lasers is created where the lasers are separated by regions of higher index for anti-guiding that enables in-phase operation with a narrow on-axis far field intensity [10]. The ion-implanted apertures can be accessed independently, leading to optically coupled, but electrically isolated VCSEL diode arrays. Modeling of leaky mode coupling between two elements with detuning [13] provides criteria for coupling when lasing wavelengths of each element are similar, producing a stable lasing supermode [14].

The ability to independently access the current injection of each element of the VCSEL is critical for controlling the phase relationship between neighboring elements of the array [15]. Furthermore, we have shown in 1 × 2 photonic crystal VCSEL arrays that we can tune the constituent laser resonances such that we can induce coherent operation [16]. The resonance tuning of photonic crystal implanted VCSEL arrays allows us to adjust for fabrication misalignment, design tolerances, and even environmental conditions to guarantee coherent operation. Here we report the generality of resonance tuning for both substrate-emitting and top-emitting geometries. We use post-fabrication techniques, such focused ion beam etching (FIBE) [17], to electrically isolate the individual array elements. Measurements of spectra and emission profiles are used identify either the localized modes from an individual element, which we call incoherent operation, or the array supermodes, which we call coherent operation.

2. Designs and Fabrication

Side view sketches of the substrate-emitting and top-emitting photonic crystal VCSEL arrays are shown in Fig. 1. The details of the fabrication procedure can be found elsewhere [10], [12] but standard processing steps are utilized [18]. The substrate-emitting VCSEL epitaxy was grown on an n-type GaAs substrate with 29-period n-type output coupler distributed Bragg reflector (DBR) mirror on the bottom, multiple quantum well active region emitting at nominally 980 nm in the middle,
and a 31-period p-type mirror on the top. On the top surface, gold contacts for each element of the array are used with a 3-micron thick gold pillar covering each lasing aperture. The gold pillars define a self-aligned implant mask. Multiple proton implantation steps at energies ranging from 200 to 490 keV define the gain apertures of the elements of the VCSEL arrays. The optical confinement is provided by a photonic crystal pattern, which is defined by optical lithography and etched by reactive ion etching. The cathode contact is evaporated onto the substrate surface only on the perimeter of the sample so that the light output is undisrupted. Finally, a quarter-wavelength SiN antireflective coating is deposited on the emission surface. Here we report the coherent properties of 1 × 2 substrate emitting VCSEL arrays.

The epitaxy of top-emitting VCSEL arrays consist of an n-type GaAs substrate with a 35-period n-type DBR bottom mirror and a 27-period p-type top mirror output coupler. The active region has multiple quantum wells designed for 850 nm wavelength emission. A broad area gold contact is deposited on the substrate for the cathode, and the top anode contacts are patterned around each array with a separate contact for each element of the array. A reactive ion etched photonic crystal again provides optical confinement, while the gain confinement is provided by a single 330 keV proton implantation step. The top-emitting array reported in this work is a 2 × 2 array and each of the four elements has a unique contact pad.

The photonic crystal patterns used to define the individual laser elements in the arrays were similar for both the substrate-emitting and top-emitting devices. Both square and hexagonal hole geometries were used, where a missing hole in the pattern corresponds to the cavity of an array element. We have previously studied the effect of hole diameter and pitch in the photonic crystal pattern in a single VCSEL to produce only fundamental mode emission [19], and similar parameters were used here. However single mode emission cannot be necessarily expected from each elements of our array, since each array element does not have the identical surrounding photonic crystal pattern. Further we have previously optimized the transverse optical coupling by modifying the hole size and/or gap between the elements; the elements of our arrays couple through gaps in the pattern, with smaller hole size near the cavities [20]. Because of the wavelength independence of the photonic crystal design [21], nearly the same designs are used for both substrate-emitting and top-emitting devices in spite of their differing nominal emission wavelength. For the substrate-emitting arrays the photonic crystal is etched 50% through the highly reflective mirror, and for the top-emitting arrays the photonic crystal is etched 50% through the output coupling mirror.

For both the substrate-emitting and top-emitting VCSEL arrays, the top layers are highly p-doped to ensure low-resistance electrical contacts. This creates the possibility for electrical crosstalk between the contact pads of neighboring elements of the array. We found in our previous work that electrical isolation is critical to separately control the cavity resonances [16]. The substrate-emitting sample often has overlapping gold pillars, which cause an electrical short between the lasing elements. Electrical isolation in this case could be improved by scratching between the pillars. Electrical isolation between the elements is also achieved using an anisotropic but shallow FIBE. The etch depth was controlled to be only through the top contact layer (approximately 700 nm) in order to minimally perturb the supermode optical mode. As an example for the top-emitting VCSEL array, before FIBE the neighboring array elements exhibited 50 Ω resistance between them, whereas after FIBE the electrical resistance increased to approximately 70 kΩ.

3. Optical Characterization of Substrate-Emitting 1 × 2 VCSEL Arrays

After fabrication and FIBE electrical isolation of the VCSEL arrays, the continuous wave output power versus injection current, the near-field and far-field mode profiles, and the emission wavelength are measured at room temperature. The substrate-emitting VCSEL arrays used a bottom contact plate with a hole for light emission suspended over an optical table so that the emission could be sent to a photodetector, fiber-coupler, imaging camera, or a goniometric radiometer. To keep the laser output from saturating the camera, the signal is attenuated by filters with varying optical densities. The output power for both the substrate-emitting and top-emitting VCSEL arrays are measured before and after the FIBE isolation. In most cases, resonance tuning was not viable before FIBE electrical
isolation, since the electrical cross talk between the elements precluded the ability to independently tune the lasing resonance in each array element.

The light output characteristics for the $1 \times 2$ bottom emitting VCSEL array before isolation is shown in Fig. 2(a), indicating a threshold current of 9 mA. Above threshold the optical output is incoherent because each element emits independently. Mechanical scratching between the elements was enough for this array to achieve sufficient electrical isolation to permit resonance tuning. Shown in Fig. 2(b) is the array output for fixed current into one element ($I_2 = 5.5$ mA) and varying the injection current into the other element ($I_1$). The nonlinear behavior of Fig. 2 arises from the modal behavior of the laser array. Fig. 2(a) has a threshold current of 9 mA, multimode behavior beginning at 12 mA, and a rollover current of 14 mA. Throughout this range the elements of the $1 \times 2$ array are incoherent with each other. Fig. 2(b) displays the light output with a single array element fixed at 5.5 mA while the second array element is biased between 0 and 7.5 mA. Each peak and valley of the light output in Fig. 2(b) corresponds to different incoherent, partially coherent, and coherent modes in the two-element array. Fig. 3 depicts the emission spectrum and near-field profiles obtained for various biasing conditions. The far fields were also observed (not shown). At the origin of Fig. 2(b) corresponding to Fig. 3(a), a single spectral peak corresponding to only one lasing element is observed. For this bias condition, the element with fixed injection current is already above threshold, and with increasing current into the other aperture, its output increases and interacts with its neighbor such that we observe multiple points of specific optical behavior, as labeled in Fig. 2(b). At various bias conditions in Fig. 2(b), the relative intensity maxima (minima) of the array output power occurs for biasing conditions generating coherent (incoherent) operation; far-field observations were consistent with regions identified as coherent operation. As discussed below, points (c), (e), and (f) in Fig. 2(b) are biasing conditions at which the cavity resonances of the two neighboring elements are tuned to spectrally overlap in order to promote a higher order coherent array mode. Conversely, points (a), (b), and (d) in Fig. 2(b) correspond to bias conditions in which each element operates independent from the other element.

When the $1 \times 2$ VCSEL array operates coherently, a single narrow lasing peak is apparent in the emission spectrum along with two near field lobes corresponding to the two array elements with one or more distinct interference fringes between them, as well as a structured far-field (not shown) with either an on-axis intensity lobe [in-phase mode for Fig. 3(c) and (f)] or an on-axis intensity null [out-of-phase mode for Fig. 3(e)] [20]. A high degree of coherence can be inferred by a structured far-field profile [22], and the bright near-field interference fringes apparent in the near-field profiles indicate anti-guided coupling of these arrays [10]. The spectral width is plotted for each spectrum as a bar in Fig. 4. Note that the points of high coherence, Fig. 4(c), (e), and (f), have the narrowest spectral...
Fig. 3. Spectra and near-fields (inset) at selected bias currents noted in Fig. 2(b) for the 1×2 substrate-emitting VCSEL array.

widths. The number of interference fringes increases with increasing current, which is apparent by comparing Fig. 3(c), (e), and (f), respectively. Coherent optical coupling between the elements also leads to relatively higher output power as expected and observed in Fig. 2(b) points (c), (e), and (f). When the 1×2 array operates with less coherence, the lasing emission is multimode due to two spectral peaks originating from each lasing element [e.g., Fig. 3(b) and (d)]. Under these conditions, the near-field fringes are indistinct, the far-field consists of overlapping Gaussian profiles, and the output power is relatively low (total intensity is the addition of the individual intensities in each element).

In Fig. 4 the spectral peak wavelengths and the observed full width at half maximum spectral width (denoted by bars) are plotted against the input current, $I_1$, for fixed $I_2 = 5.5 \text{ mA}$. An overall trend, shown by the solid and dashed lines fit over the data in Fig. 4, indicates the spectral evolution of the array, which agrees with our previous research [16]. The solid line follows the emission of
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Fig. 5. Spectrum of 2 × 2 top-emitting array and far-field profile when elements are (a) connected in parallel with 10.0 mA total injection current; and (b) separately electronically tuned to coherence with element currents of (1.67, 1.99, 2.10, 1.84) mA.

the element held at a constant current and the dashed line traces the emission from the element with varying bias. The emission wavelengths from both elements redshift as the current increases, because of the accompanying increase in temperature and thus the laser cavity refractive index. Note that with (I₁, I₂) currents of (3.2, 5.5) mA injected into the array, element two lases (incoherently) and element one is near threshold, consistent with the array threshold current observed in Fig. 2(a). At the injection currents of (4.2, 5.5) mA the cavity resonances of both elements is approximately 978 nm, which enables highly coherent array emission, as indicated in Fig. 3(c). The coherent operation at (5.4, 5.5) mA and (6.2, 5.5) mA, corresponding to Fig. 2(e) and (f), respectively, do not occur for identical cavity resonance and do not follow the trend shown by the dashed line in Fig. 4. However this behavior is consistent with the resonance overlap between the fundamental mode of one element and a higher order mode of the other element, and is in agreement with the expected number of interference fringes and the resultant in-phase or out-of-phase far field [16]. This evolution of the emission coherence agrees with prior measurements of top-emitting arrays, and provides a simple approach for controlling and/or digitally modulating the far-field profile.

The continuous wave output power from a VCSEL is affected by the junction temperature and the accompanying spectral red-shifts and spectral overlap between the quantum well gain and the cavity resonance [19]. For arrays this is further complicated by differences between the spatial overlap between the gain and the individual (incoherent) cavity modes and the (coherent) supermodes. Nevertheless, comparisons between Fig. 2(a) and (b) can be made. Note the maximum output power in Fig. 2(b) is nearly 0.6 mW at a total input current of 11 mA, which is consistent with the incoherent power at 11 mA in Fig. 2(a). In Fig. 2(b) there is significant reduction of power at currents between the regions identified as highly coherent [e.g., I₁ = 6 and 7 mA in Fig. 2(b)]. The two elements remain coupled (as determined from the observed structured far-field), but the supermode evidently has a poor spatial overlap with the gain yielding dramatically less coherent output as compared to the incoherent power for the same total current input [e.g., I = 11.5 and 12.5 mA in Fig. 2(a)].

4. Optical Characterization of Top-Emitting 2 × 2 VCSEL Arrays

Top-emitting 2 × 2 arrays are characterized before and after the FIBE electrical isolation. The optical performance of the array before isolation is similar to the case of the four contact pads connected in parallel with an external current supply. Due to slight variations of the series resistance in each element, the current injection into each element varies. Specifically, the spectrum at 10 mA total injection current into all elements connected in parallel is shown in Fig. 5(a), which exhibits
four separate spectral peaks, one from each element, where each element emits into a Gaussian mode, corresponding to incoherent operation.

Resonance tuning to coherence is done using the following procedure. Driving the elements of the array with independent currents, the array spectrum is observed and the currents into the four elements are varied, until all four elements are resonantly tuned to the same resonance, creating a single narrow linewidth emission peak, such as shown in Fig. 5(b). Each element of the array has a current tuning range of approximately 5 mA, resulting in approximately 2 nm of spectral tuning. We pick one element at a time and vary the injection current until a coherent bias point is found. The bias point when all elements are spectrally resonant produces the coherent out-of-phase far-field shown in Fig. 5(b). The out-of-phase coherent mode is preferred in this array due to the FIBE modification producing higher optical loss and thus encouraging a null in the wavefunction between the elements. The unbalanced intensities in the four far-field peaks will arise from unintended size variations between the elements, as well as phase differences between adjacent elements that are not exactly \( \pi \)-phase separated \[4\], \[15\]. Further analysis of the modal behavior would require simulation of the anti-guided coupling \[10\] and the spatially dependent optical gain in multiple element arrays.

When any one of the four elements is spectrally detuned from the condition of Fig. 5(b), coherent operation cannot be achieved. Moreover, multiple sets of bias currents create coherent emission, albeit at different resonant wavelength. Variation of the optical cavity and/or series resistance of the elements likely leads to different bias currents into the array elements, and thus coherent operation of our VCSEL arrays can be maintained in presence of fabrication imperfections and environmental changes.

5. Conclusion

This work demonstrates coherent operation via resonance tuning in \( 1 \times 2 \) substrate-emitting VCSEL and in \( 2 \times 2 \) top-emitting VCSEL arrays. Hence using independent electrical injection for each laser element, we show in general we can spectrally tune each array and yield coherence in arrays that are otherwise incoherent. This flexibility adds robustness to laser arrays, with a guarantee of coherence in spite of imperfect fabrication, environmental changes, or other imbalanced individual lasers within the array. Recently resonance tuning has been applied to achieve record small signal bandwidth \[4\]. Exploiting the capability of resonance tuning will create both new VCSEL applications and potentially improve their performance in existing applications.

References


