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Breakthroughs in Photonics 2014: Coherent Vertical-Cavity Surface-Emitting Laser Arrays

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Abstract: Coherently coupled vertical-cavity surface-emitting laser (VCSEL) arrays exhibit novel optical properties, which can be exploited for applications. After a brief review of prior semiconductor optically coupled microcavity laser arrays, we discuss recent advances in photonic crystal implanted vertical-cavity laser arrays. We report the ability to tune these VCSEL arrays with appropriate geometry into coherence by ensuring spectral overlap between the resonance of each element of the array. Using the independent current injection into the elements of the coherently coupled array, the relative phase of the array elements and the output beam coherence can be tuned. Coherently coupled microcavity arrays are shown to offer the potential for ultrahigh-speed digital modulation.

Index Terms: Semiconductor laser arrays, vertical cavity surface emitting lasers.

1. Introduction

Vertical cavity surface emitting lasers (VCSELs) are the semiconductor light source of choice for low-cost, high-performance optical communication links and position sensing. It has been estimated that more than a billion VCSELs have been deployed to date in commercial applications [1]. One and two-dimensional VCSEL arrays have also been used for parallel channel interconnects, but in these arrays the individual lasers are designed to operate independent and do not optically interact. However, it has long been recognized that an optically coupled laser array will have unique properties that may enable new applications.

One challenge for coherently coupled microcavity laser arrays is to pixelate the array elements in a manner that permits strong optical coupling between neighboring elements. Coherent VCSEL arrays have been previously demonstrated using a variety of approaches, which include etching into the distributed Bragg reflector mirrors between the array elements [2], [3], etching between the elements combined with checker-board phase-adjusting layers [4], deposition of metal grids over the arrays [5]–[7], and creating high index anti-guides between the array elements [8], [9]. A common disadvantage of these approaches is that the out-of-phase mode, with an on-axis null in the far zone, is often favored to lase. This happens because the manner in which the array is pixelated creates a distinct refractive index perturbation which tends to force

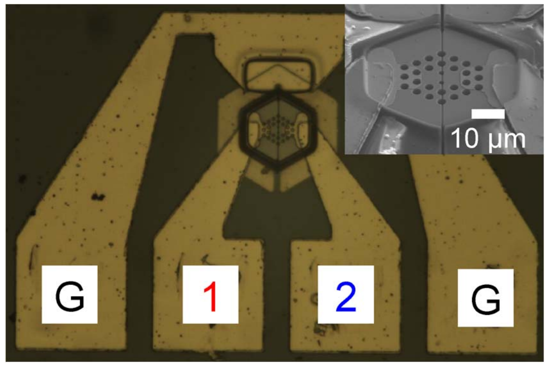

Fig. 1. Optical and scanning electron microscope image of 2 × 1 photonic crystal implanted VCSEL array.

the electric field to a null between the elements, so that adjacent elements are necessarily 180° out-of-phase, which leads to the less desired out-of-phase far-field mode profile. Only for the phase-adjusted [4] and regrown anti-guided [8], [9] VCSEL arrays has this difficulty been consistently overcome but at the expense of complex fabrication.

To permit in-phase coupling between the VCSEL array elements, etching a photonic crystal pattern with multiple defects (missing holes) to define the array elements [10] or using ion-implantation to define gain-guided array elements [11] has also been employed. The former approach produces coherent VCSEL arrays with a low fabrication yield [12], while the latter arrays operate coherently only near lasing threshold. Combining a photonic crystal with its minimal index perturbation between the elements to define the optical cavities, with an ion implant-defined pixelated gain, enables a robust coherent VCSEL array [13]. The implant-defined gain regions create electrical isolation between the array elements. The resulting independent current injection has recently been shown to permit resonance tuning of the elements of the array such that virtually any photonic crystal implanted VCSEL array with appropriate geometry can be tuned into coherent operation, making these phased arrays appropriate for new applications.

2. Photonic Crystal Implanted VCSEL Array

Laterally coupled photonic crystal implant VCSEL arrays have been demonstrated where the phase relation between the elements can be tuned. The simplest such structure is a 1 × 2 VCSEL array shown in the images of Fig. 1. Both elements of the array can be independently contacted with the high speed pads (ground-signal-signal-ground) that are evident in Fig. 1. The photonic crystal (see the inset of Fig. 1) provides stable index guiding for the array and greater optical loss for higher order modes. The leaky-mode coupling between the cavities is engineered via the photonic crystal hole pitch and diameter, such that the emission will favor either the in-phase or out-of-phase far field mode (before electronic tuning) [13]. This structure simultaneously enables independent current injection into either cavity, which can be exploited to tune virtually every array into coherence and control of the phase between the elements.

The spatially resolved emission and the far-field profiles for the phased VCSEL array shown in Fig. 1 are shown in Fig. 2 for various injection currents into the array elements [14]. By preferential current injection into one element with respect to the other, we change the cavity refractive index for that element, thus varying its natural resonance such that both elements have the same resonance wavelength, and thus the array is tuned into coherent operation [14]. For example in Fig. 2(a), the natural resonance of element 1 has shorter wavelength than element 2; with increasing current into element 1, its resonance can be locked to that of element 2, and as a result we obtain the single-mode emission with an "out-of-phase" far-field mode as seen in Fig. 2(b). With further current increase into element 1, it resonance wavelength becomes longer than that of element 2, with the result of incoherent operation of two overlapping

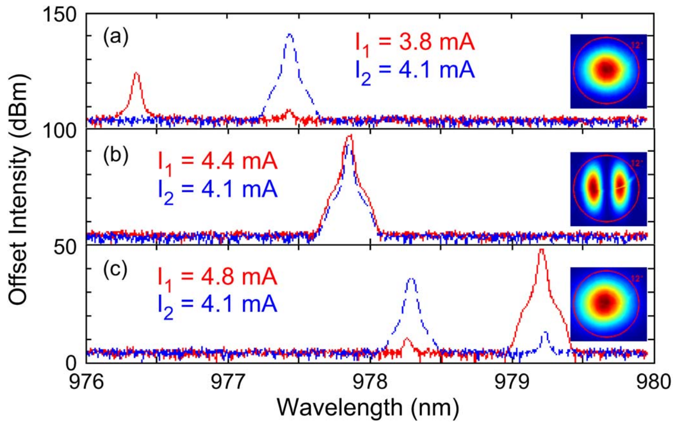

Fig. 2. Spatially resolved spectra and far-field intensity profile for three sets of injection current into elements 1 and 2.

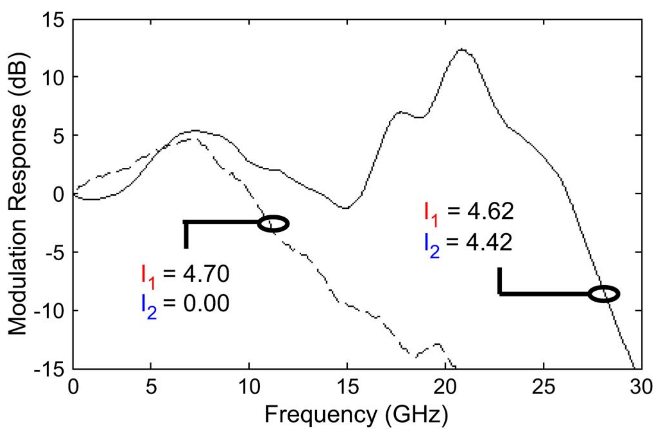

Fig. 3. Small signal modulation response for 1×2 VCSEL array for two sets of injection currents into elements 1 and 2.

Gaussian modes apparent in the far-field as in Fig. 2(c). In this manner, phased VCSEL arrays with appropriate geometry can be tuned into coherence by insuring spectral overlap between the resonances of the elements of the array through independent current injection into the array elements. Note that there is not one unique combination of injection currents that lead to coherent operation; rather, the array can often be tuned to coherence over a large range of biasing conditions [14].

3. Applications

Through independent current injection into each element, we can tune the photonic crystal implanted VCSEL array into coherent operation. When the array is locked into coherence, we find the individual injection currents can be slightly varied, and the array remains optically coupled. However, the current variation enables the phase between elements to be tuned [15] which is manifest in the far-field with the emission angle of the main emission lobe varying. Hence electronic beam steering can be achieved with 0.83 π/mA steering sensitivity to current as well as 10^8 degrees/s steering speed, both of which are record values for semiconductor lasers [16].

Moreover, it has been found that optically coupled VCSEL arrays exhibit significantly enhanced modulation bandwidths [17]–[19]. Transversely coupled VCSEL arrays formed from oxide-confinement that operate multi-mode have demonstrated small signal bandwidth enhancement to greater than 20 GHz, as well as stable large signal modulation as high as 36 Gb/s [17], [18]. Fig. 3 shows the small signal modulation response of the 2×1 photonic crystal implant VCSEL array of Fig. 1 under different bias conditions. With no bias to one element [or under incoherent operation, such as shown in Fig. 2(a) and (c)], the typical small signal modulation of an individual VCSEL is obtained (e.g., dashed curve in Fig. 3). However, when the array is biased into coherence, we find that the small signal bandwidth can be significantly enhanced with a higher frequency resonance apparent (e.g., solid curve in Fig. 3). Note that the array can tuned into coherence at relatively high bias currents, which creates single mode emission with relatively high output power. The array elements are defined by conventional implantation apertures with diameters such that the operation current density is below 10 kA/cm^2, which implies reliable device lifetime. The best performance achieved to date is 37 GHz small signal bandwidth with more than 3 mW of single mode (0.042 nm RMS spectral width) emission at 8 kA/cm^2 current density [19].

4. Summary

Coherently coupled VCSEL arrays have been pursued for nearly three decades to overcome significant fabrication and yield challenges. A recent device structure that relies on conventional VCSEL fabrication processes is the photonic crystal implanted VCSEL array. It has been found that coherent operation of these phased VCSEL arrays can be reproducibly achieved with high yield. Independent current injection into phased photonic crystal VCSEL arrays can drive the arrays to exhibit either coherent or incoherent operation. Moreover, controlling the phase relationship between the pixels of a coherently coupled VCSEL array can create unique properties. For example electronic beam steering can be performed with record phase shift sensitivity with current producing ultrafast beam steering. In addition, dual element VCSEL arrays have exhibited significant modulation bandwidth enhancement. Therefore with the added complexity of two (rather than one) bias currents, high power single mode emission from VCSEL arrays operating at $>$ 30Gb/s and potentially much higher bandwidth may be appropriate for data center optical communication applications.

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