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Alec C. Sills
Rose-Hulman Institute of Technology

Gavin N. West
Rose-Hulman Institute of Technology

Eryn A. Fennig
Rose-Hulman Institute of Technology

Mike P. Grimshaw
nLight Corporation

Matthew T. Johnson
University of Illinois at Urbana-Champaign

See next page for additional authors

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Authors
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In-Phase Coherently-Coupled Optically-Pumped VECSEL Array

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Manoj Kanskar, Kent D. Choquette, and Paul O. Leisher

***Abstract*—We report on an optically pumped vertical-external-cavity surface-emitting laser array exhibiting coherent coupling. Imaging of the far field shows interference consistent with in-phase coherent coupling, and a majority of total power is present in the central on-axis lobe. The physical mechanism of operation is attributed to diffractive coupling, wherein a small portion of the light emitting from each emitter is shared with adjacent emitters of the array.**

***Index Terms*—Diode lasers, coherent coupling, VECSEL arrays.**

I. INTRODUCTION

Vertical External Cavity Surface Emitting Lasers (VECSELs, also commonly referred to as optically-pumped semiconductor lasers, or OPSLs) are an emerging laser class which combine the flexibility of quantum-well based gain materials, the brightness of thin disk lasers, and can be scaled in two dimensions. Because the output coupler is external, the focusing of pump light onto the VECSEL chip itself can be accomplished through multiple means. Integrated two dimensional arrays offer an attractive approach for power scaling due to compatibility with low cost manufacturing and test processes. In this work, a microlens array for this application allows for immense scalability of the overall design, and could provide a much more cost efficient system.

Limitations of semiconductor lasers include the often poor beam quality of edge-emitting systems [1] and the low output power of surface-emitting lasers [2], and are inherent in the design architectures of the systems themselves. VECSELs offer improved single-mode power scalability through extending the resonant cavity using external feedback optics [3]. While commonly optically pumped, these devices are also compatible with direct electrical injection, making them attractive sources for a variety of applications such as communication and pumping [4].

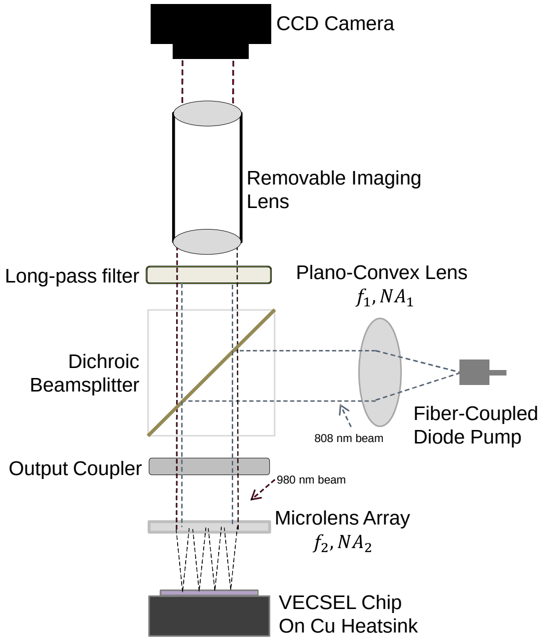

Fig. 1: Experimental setup of the optically-pumped VECSEL array. The imaging lens was used for near-field measurements and removed for far-field measurements.

Previous work with VCSEL arrays [5, 6] has allowed for their successful commercialization, in both incoherent and coherent configurations. While incoherent 2D arrays offer total power scalability [6, 7], they do not provide for brightness scaling. Coherent arrays allow both power and brightness scaling [8], but typically require complicated external optics such as an accurately placed Talbot mirror or spatial filters. In some instances, phase control at the individual emitter level is required.

In this work, we demonstrate a simple in-phase coherently-coupled 2D VECSEL array. The physical mechanism responsible for coupling is diffraction – light emitted from each element of the array is partially shared by other elements of the array. This demonstration of a simple method for a coherently-coupled array shows great promise for improvement upon previously complicated coherent array systems and continued increase in scaling of both power and brightness.

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A. C. Sills, G. N. West, and P. O. Leisher are with Rose-Hulman Institute of Technology, 5500 Wabash Ave., Terre Haute, IN 47803 (phone: 812-877-8824; e-mail: pleisher@ieee.org).

E. A. Fennig is now with the University of Rochester, 275 Hutchinson Rd., Rochester, NY 14627.

M. Johnson is now with the US Air Force.

M. Grimshaw is with nLight Corporation, 5408 NE 88th St. Bldg E, Vancouver, WA 98665.

K. D. Choquette is with the University of Illinois at Urbana-Champaign, 208 N. Wright St., Urbana, IL 61801.

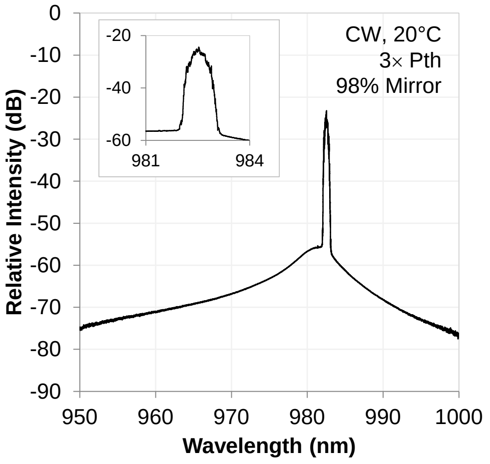

Fig. 2: Optical lasing spectrum measured under CW operation.

II. EXPERIMENT

The design of the VECSEL epitaxy, based partially on the design reported in [9], consists of a highly reflective (38-pair) bottom DBR and partially reflective (5-pair) top DBR composed of alternating layers of $Al_{0.90}Ga_{0.10}As$ and $Al_{0.12}Ga_{0.88}As$. The active region contains a total of fourteen compressively-strained 50 Å InGaAs quantum wells surrounded by 30 Å GaAsP strain compensating barrier layers. The quantum wells were arranged into seven pairs separated by 120 nm thick $Al_{0.12}Ga_{0.88}As$ waveguiding layers so as to center each pair about the peak of the optical standing wave profile in the 4λ cavity. To maintain low optical loss, none of the layers were intentionally doped. The structure was grown bottom-up with an InGaP etch stop layer inserted between the top DBR and substrate wafer. A sample of the wafer was cleaved to 10 mm x 10 mm, thinned to approximately 150 μm total thickness, In soldered to CVD diamond heat spreaders, and the remaining substrate was removed using chemical etching. The chip-on-submount was then mounted to a Cu heatsink for testing. No additional patterning or processing of the chip was performed.

The setup for the optically pumped VECSEL is shown in Fig. 1. A high-power 808 nm diode laser module (fiber coupled, 200 μm, 0.2 NA) was used as the pump source. The optical pump light was collimated with a 40 mm focal length biconvex (best-form spherical) lens. The pump light was then introduced to the lasing cavity by means of a dichroic beamsplitter that has >90% reflectance at the pump wavelength of 808 nm and >90% transmission at the lasing wavelength of 980 nm. The laser resonator consisted of the VECSEL chip mounted on a heatsink, the microlens array, and the output coupler mounted to create an overall cavity length of 5 to 12 mm (this length was adjusted to assess the impact of divergence loss on the lasing characteristics). The output coupler used was a planar $(\lambda/10)$ dielectric mirror with a nominal 98% reflectance at 980nm (the mirror was found to transmit 77.5% of the 808 nm pump light). The microlens array used for the laser cavity had a focal length of 1.0 mm, a numerical aperture of 0.12, and its circular elements were arranged in a hexagonal grid, with 2000 elements per square centimeter. Unabsorbed residual pump light that passed through the beamsplitter was removed using a highly reflective (99.97%) long pass filter with cutoff wavelength 880 nm. A CCD camera was used for imaging of the beam. The design of the laser cavity (pump collimator and lens array) was based on a compromise among the following constraints: 1) matching the pump spot to the fundamental mode lasing spot for each emitter, 2) limiting the total number of lasing elements to keep the total threshold power within the capability of the pump source, and 3) using readily available commercial-off-the-shelf optics.

Pumping was performed in quasi-continuous wave (QCW) mode using a pulse duration of 100 µs and 10% duty cycle. This pump condition was chosen to allow internal-self heating similar to what would be experienced under CW operation, while protecting the chip from overheating due to the relatively poorly integrated heatsink system. Scaling to continuous wave operation would be possible with improved heatsink design and attachment processes. All experiments were performed at 20°C.

III. RESULTS

The array reached threshold at an absorbed pump power of 6W, and the results reported herein were measured at 3X threshold. The lasing spectrum was measured using a commercial optical spectrum analyzer and is shown in Fig. 2 (note that this was measured CW in order to prevent thermal chirp in the observed spectrum). The array operates single mode with no discernible peaks above the spontaneous background 30 dB below.

The plane of the microlens array was imaged with unit magnification using a 4f lens configuration. An image was taken sub-threshold in order to assess distribution of the pump intensity across the array and is shown in Fig. 3(a). The far-field intensity distribution was obtained by removing the imaging lens from the camera system and is shown in Fig. 3(b). A circle corresponding to diffraction limit (based on the calculated theoretical beam waist radius at the lens array of 62 μm) is drawn for reference. As shown, there is a clear interference pattern visible within the diffraction limit ring, which is strongly indicative of coherent coupling. For this case (9 mm mirror array separation), approximately 60% of the total output power is present in the central on-axis lobe. A simulated far field image is also shown for comparison in Fig. 3(c). The image was obtained using the Fraunhoffer approximation to propagate a 7-element hexagonal array comprised of elements with 62 μm beam waists and a pitch of 250 um to the far field, assuming the elements are mutually coherent [10]. The disagreement between the simulated and observed far-field images is attributed to imperfections in the imaging system.

The calculated Talbot self-imaging condition [11] for this configuration corresponds to a mirror-array separation distance of 64 mm, making it an unlikely candidate for explaining the observed coherent coupling. Furthermore, the wide separation (250 μm) between adjacent emitters in the plane of the active region rules out evanescent coupling. The physical mechanism

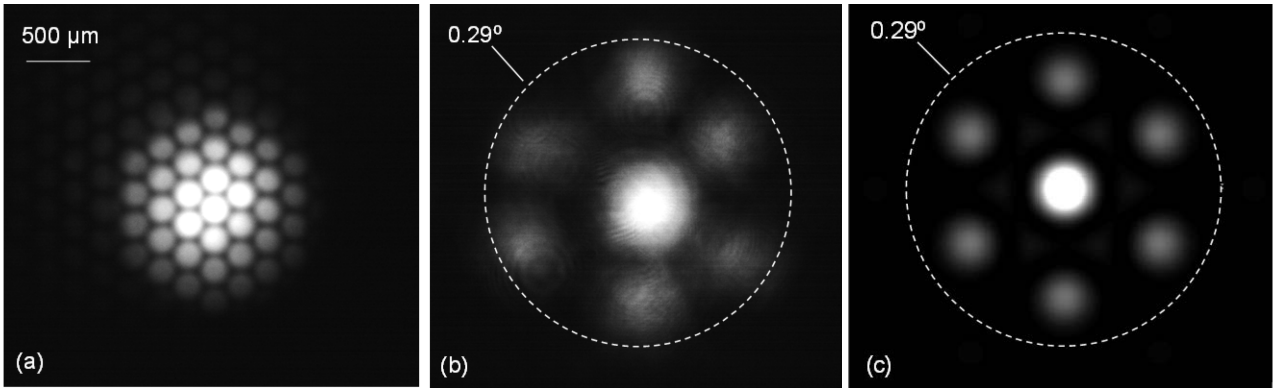

Fig. 3: (a) Image of the laser array observed at the position of the microlens array. (b) Far field image of the laser emission. The image was taken under QCW operation at pump power of 3X threshold. (c) Simulated far field image from a 7-element hexagonal array of 980 nm laser emitters with 62 µm beam waists, 250 µm element pitch, and assuming mutual coherence between the elements.

responsible for coherent coupling is attributed to diffractive coupling – a small portion of the light from each emitter is shared with adjacent emitters due to the divergence of the beam inside the cavity.

To further investigate coherent coupling effect, a series of experiments were performed wherein the separation of the output coupler and the lens array was varied in order to modify the diffraction loss (and therefore coupling) in the cavity. Fig. 4 shows the effect of varying this distance on both the overall output and the relative amount of output present in the central lobe. As the mirror-array separation is increased, the diffraction loss of the laser cavity increases strongly, leading to a reduction in the normalized output power. This also has a second-order effect of increasing the beam waist diameter at the lens array which results in a greater proportion of the total output in the central on-axis lobe, as would be expected for a diffractively coupled coherent laser array.

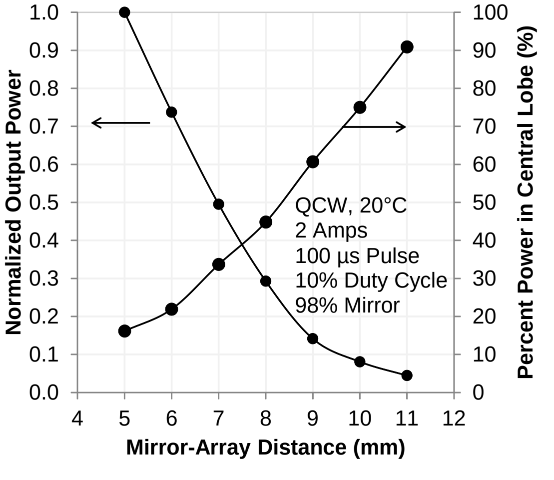

Fig. 4: Laser characteristics as functions of cavity length between output coupler and lens array.

IV. SUMMARY

An optically pumped VECSEL array has been demonstrated and exhibits in-phase coherent coupling. The origin of coherence between elements is attributed to diffractive coupling. Future work will focus on improving the power conversion efficiency to allow scaling to higher power under CW operation, scaling to larger arrays, and further investigation of the coupling, including modeling and inteferogram assessment of the degree of coherence.

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