In-Phase Coherently-Coupled Optically-Pumped VECSEL Array

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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].

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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introduced to the lasing cavity by means of a dichroic wavelength of 808 nm and >90% transmission at the lasing biconvex (best-form spherical) lens. The pump light was then wavelength of 980 nm. The laser resonator consisted of 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 980 nm (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 $\mu$s 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 within 30 dB background.

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 Fraunhofer approximation to propagate a 7-element hexagonal array comprised of elements with 62 μm beam waists and a pitch of 250 μm 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
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.

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 interferogram assessment of the degree of coherence.

**REFERENCES**


