

Collimating Diode Laser Beams from a Large-Area VCSEL-Array Using Microlens Array

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Opticis Co., Ltd
EXHIBIT 1011
IPR Petition for
U.S. Patent No. 7,198,416

Abstract—In this letter, we demonstrate the fabrication and bonding of a 1 cm × 1 cm monolithic two-dimensional (2-D) vertical-cavity surface-emitting laser (VCSEL) array. We coupled the array to a matched microlens array to individually collimate light from each laser. We found the beam divergence of the collimated array to be 1.6° ($1/e^2$) for the entire array. Using a 1-cm diameter F2 lens, we were able to focus the collimated beams to a spot of 400 μm in diameter and to couple more than 75% of the array power into a 1-mm core fiber. Our results show that it is possible to uniformly bond large area VCSEL arrays to heat sinks, and to collimate light from each element into parallel beams using a single 2-D microlens array. Our results also show that the brightness of the focused beam can be further increased with a lens to near 10^5-W/cm^2 Steradian, a level that is useful for many high-power applications.

Index Terms—Monolithic microlens arrays, monolithic VCSEL arrays, optical fiber coupling.

I. INTRODUCTION

VERTICAL-CAVITY surface-emitting laser (VCSEL) structures potentially can be used in building high-power arrays for printing, laser radar, optical communications, and pumping of solid state and fiber lasers. However, to date no one has demonstrated a practical VCSEL system with the power density and brightness required for such applications. Useful VCSEL arrays must: 1) increase their peak power density; 2) increase brightness; 3) scale to dimensions to square centimeters; and 4) decrease fabrication costs to below that of edge-emitting laser (EEL) arrays. As for power density, recently Grabherr *et al.* reported VCSEL power densities exceeding 300 W/cm^2 from a 23-element array [1]. In a previous paper, we demonstrated VCSEL power in excess of 2-W continuous-wave (CW) and 5 W pulsed from a 1000-element array [2]. In this letter, we concentrate on brightness and scalability and describe the design and performance of a full 1-cm² VCSEL array. To the best of our knowledge, this is the largest two-dimensional (2-D) monolithic VCSEL array reported to date.

For optical pumping of solid state and fiber lasers, there are stringent requirements on the power and brightness of the

pump source. The brightness requirements for optical pumping are typically in the range of $10^4\text{--}10^5\text{ W/cm}^2$ Steradian. Given that the minimum power required to pump any solid-state or fiber laser is in the watt range or greater and that the optical power generated by the individual emitter is normally in the $10^{-3}\text{--}10^{-1}\text{ W}$ range, output from many emitters must be combined to reach the power required for these applications. The 2-D EEL arrays currently manufactured by the industry are typically constructed by directly bonding rows of laser bars on a heat-sinking sub-mount. Because it is not possible to position each laser bar, on the sub mounts, with the level of precision required for parallel optical alignment, it is not possible to efficiently collimate light from an EEL array using a single 2-D lens-array. To collect laser beams generated from an EEL array, banks of cylindrical lenses must be used. Each lens is aligned individually to the corresponding laser bar (or row of pre-aligned bars). In this work, however, using a single 2-D microlens array, we were able to collect light from an entire 1-cm² VCSEL array. This enabled us to increase the brightness of the VCSEL arrays to within 20% of the theoretical limit (i.e., the brightness of the individual sources).

II. VCSEL/LENS ARRAYS DESIGN AND ASSEMBLY

We used a bottom-emitting VCSEL structure with 22 bottom DBR mirror pairs of AlAs–GaAs and 30 top mirror pairs of Al_{0.7}Ga_{0.3}As–GaAs. The active region consists of three InGaAs quantum wells (QW's). We designed the wafer for low-threshold operation at 950 nm and did not optimize it for high-power operation. Our array elements were oxide-confined VCSEL's with 50- μm mesas and 10- μm apertures. We chose the aperture size to maximize the efficiency of the structure and to minimize nonuniformity between array elements. We fabricated arrays of 40×40 VCSEL's with 250- μm center-to-center spacing. The overall size of the monolithic laser array was 1 cm × 1 cm × 0.3 mm.

We mounted the VCSEL array *p*-side down onto an actively cooled copper block and AR coated the back side with Si₃N₄. Fig. 1 shows typical light output versus current (*L–I*) and voltage versus current (*V–I*) characteristics for a 1 cm² VCSEL array, with 40×40 lasers, measured at 1 °C heatsink temperature. We measured the optical spectra of the entire array at 4 A and found the spectral width to be approximately 6 nm (from 934 to 940 nm). As expected, the spectra shifts toward longer wavelengths with increasing drive current.

Manuscript received December 7, 1998; revised February 9, 1999. This work was supported by the University of California under the UC Campus Laboratory Collaborations Program and by the U.S. Department of Energy under Contract W-7405-Eng-48.

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Publisher Item Identifier S 1041-1135(99)03604-6.

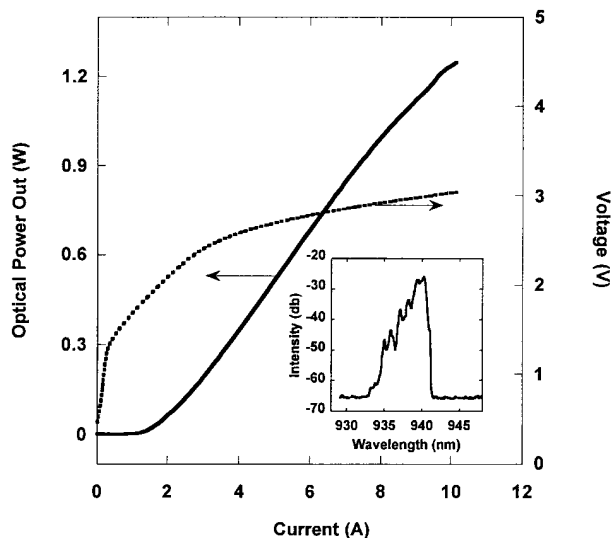


Fig. 1. The L - I characteristics of all the lasers of the array driven in parallel. Inset, the spectra of the array at 4-A drive current.

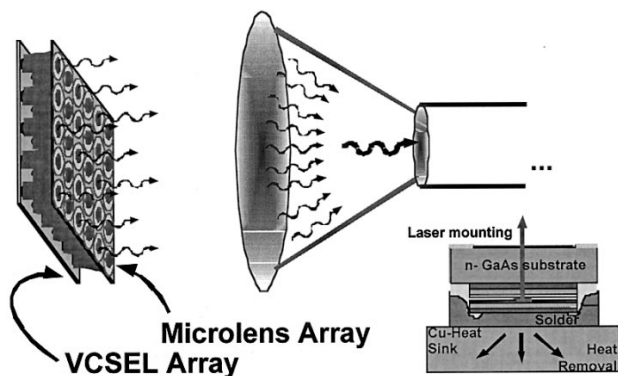


Fig. 2. A schematic of the 1-cm² array coupled to the microlens array and to a fiber.

We used a fused silica microlens array, with each individual lens having a 0.357-mm radius of curvature and a 0.776-mm focal length. The pitch between lenses is also 250 μ m, matching the configuration of our 2-D VCSEL array. The overall fill factor of the lens array is 96%. Fig. 2 shows the cross-sectional view of an individual VCSEL, and a simple schematic of the laser/lens arrays arrangement.

With large scale laser arrays, to achieve high power and brightness, all array elements must operate in parallel. Thus, for the array to be efficient, it is crucial that the individual devices have uniform characteristics [3] and that the entire array be uniformly bonded onto the heatsink. During the course of this work, we successfully fabricated several large-area (1 cm $\times$ 1 cm) VCSEL arrays. Bonding the centimeter-scale VCSEL array to a Cu cooling block was challenging because GaAs and Cu have large differences in thermal expansion coefficients. Nevertheless, we were able to bond the monolithic VCSEL array uniformly onto the cooling block using a thin layer of Pb-Sn solder without additional bonding additives [4]. Earlier results from our free-standing VCSEL's show very little variation in both threshold current and voltages [2]. The maximum output power of the individual emitters in the array was also uniform, in the 1.6–1.8-mW CW range.

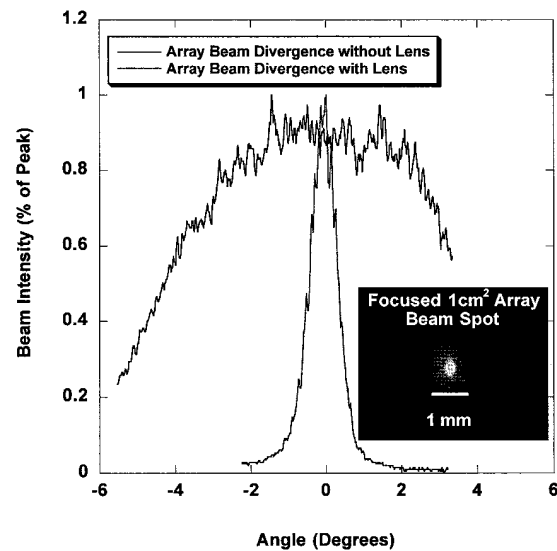


Fig. 3. The beam divergence from the laser array: without microlens 8.8° FWHM, with microlens 0.8° FWHM. Inset shows the focused spot from all the beams of the 1600 lasers focused to a 400 μ m diameter spot.

We used wavelength measurements to track the temperature variations of individual elements of the array. The thermal rollover for all elements of the array occurred simultaneously as the array, and each individual laser element, approached 80 °C. Thus, we successfully demonstrated that the bonding and heat sinking was uniform across the sample.

III. BEAM DIVERGENCE FROM THE INTEGRATED ARRAYS

To determine the focus-ability of our laser devices, we measured the beam divergence of the entire array under two different configurations. Fig. 3 shows the focused beam spot and intensity profile of laser beams generated by the 1-cm² array measured in the far field. We found the beam divergence measured without the microlens to be about 8.8° [full-width at half-maximum (FWHM)], while the beam divergence measured with microlens array was found to be 0.8° FWHM and 1.6° ($1/e^2$), which is in good agreement with the theoretical value of 0.7°. Using the 2-D microlens array, we reduced the beam divergence of the entire array by nearly an order of magnitude.

Using a 2-in-diameter F2 lens, we were able to couple nearly 75% of the array beam into a large core silica fiber. The numerical aperture of the 1-mm-diameter core fiber was 0.22. Fig. 4 shows the fiber coupling efficiency observed at various input powers. We found that the coupling efficiency, defined as the fraction of array output delivered by the fiber, is approximately 75% during the entire range of operation. We believe that we can further improve the coupling efficiency (to near 90% level) by AR coating the fiber-tips and modifying the VCSEL design to better match the numerical apertures of the overall system.

IV. BEAM BRIGHTNESS

As reported earlier, we have fabricated several watt-class VCSEL arrays and obtained more than 2-W CW from these

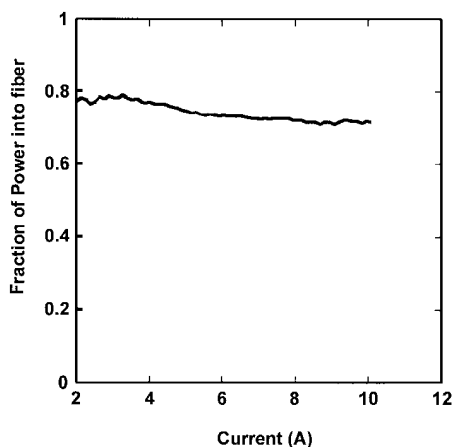


Fig. 4. The fraction of the total power of the array that is coupled into a 1-mm core fiber as a function of drive current.

monolithic devices [2]. The power densities obtained from these arrays were typically in the 30–150 W/cm² range. Using the microlens array described in this letter, we were able to collimate and focus the output from the centimeter-scale array to a spot smaller than 0.5 mm in diameter and, thus, increase the array brightness by a factor of 150. We estimated the power density and brightness of the focused beam to be about 10- and 40-kW/cm² Steradian, respectively. We measured the power of the individual VCSEL in the array driven at high power to be approximately 1 mW and their angular divergence 6°–8°. The calculated brightness of the individual VCSEL's was 50-kW/cm² Steradian. Thus, using a 2-D microlens array, we were able to preserve as much as 80% of the brightness from the individual lasers. With improved cooling and optimal wafer design of higher wall-plug efficiency, we anticipate that we

will be able to increase the power density to a level comparable with that of EEL arrays.

V. CONCLUSION

We demonstrated the first centimeter-scale VCSEL array. Using a single microlens array, we were able to collimate the light beams from the entire laser array, increasing the array brightness by a factor of 150. Using an F2 lens we were able to concentrate the entire beam to a spot of 400 μ m in diameter and couple more than 75% of the VCSEL beam into a 1-mm-diameter core fiber. Our results show that it is possible to bond large area VCSEL arrays to heat sinks, and to run the entire arrays (with >1000 elements) in parallel. We also showed that it is possible to efficiently couple the light from an entire 1-cm² array into an optical fiber using a single microlens array and one bulk lens. Using a 2-D microlens array, we were able to increase the array brightness to about 40 kW/cm² Steradian, a level of brightness that is useful for many high-power applications.

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