Scalable high-power, high-speed CW VCSEL arrays

R. Safaisini, J.R. Joseph, G. Dang and K.L. Lear

A demonstration of a high-power, high-speed 980 nm vertical-cavity surface-emitting laser array with continuous-wave power of greater than 120 mW and frequency response over 7.5 GHz at room temperature is reported. Experimental results show that copper plating the array elements and flip-chip bonding provides effective thermal management as well as offering uniform current distribution at microwave frequencies. This is verified by the radial dependence of modulation bandwidth. These arrays may be useful for short-range light detection and ranging or free-space optical communications systems.

Introduction: Vertical-cavity surface-emitting laser (VCSEL) arrays are promising light sources for different high power applications. Although edge-emitting lasers inherently have higher output power than VCSELs, many advantages of VCSELs such as low manufacturing cost, good power conversion efficiency, large-scale monolithic two-dimensional array formation, and circular beam profile have made them an alternative for edge-emitting lasers. High-power semiconductor lasers are suitable for different applications such as laser-based projection displays [1], short-range free-space optical communication [2], and light detection and ranging (LIDAR) systems [3]. In addition to high optical power, high frequency operation is of great importance for the last two applications. High-speed VCSELs have the potential to improve the data transmission rate and imaging resolution for optical communication and LIDAR systems, respectively. A 4 × 8 array of high modulation frequency 850 nm InGaAs VCSELs was previously reported for parallel optical interconnects [4]. Characterisation of individual 6 μm active diameter lasers in that array demonstrated 7 mW output powers and 11 GHz 3 dB bandwidths, but combined operation of elements in the array was not reported. Different groups are also working on high-power, watt regime VCSEL arrays but have not reported array frequency responses [5–7]. This Letter presents a uniform 28-element, 120 mW VCSEL array with a drive current limited 7.5 GHz bandwidth.

Structure: Arrays of high-speed, 980 nm high-power bottom-emitting VCSELs were fabricated. An 18 μm active diameter in a 24 μm mesa forms a circularly-shaped VCSEL array with 70 μm device pitch. These single VCSELs are electrically connected to form a single high-power, high-speed light source. A parallel configuration for both signal and ground paths reduces the series resistance and inductance of the flip-chipped array. A higher-power VCSEL can be achieved by increasing the active area of the laser. However, it reduces the modulation frequency which is inversely proportional to the square root of the effective volume of the mode at fixed device current.

The molecular beam epitaxy layers for the lasers were grown on an *n*-type GaAs substrate. The *n*-type bottom mirror consists of a 23-period Si-doped GaAs-$Al_{0.86}Ga_{0.14}$ As distributed Bragg reflector (DBR). The active region contains three 8 nm $In_{0.18}Ga_{0.82}$ As quantum wells. The 27-period *p*-type top mirror employs a C-doped GaAs-$Al_{0.86}Ga_{0.14}As$ DBR. The oxide layer is formed from a single low index $\sim\lambda/4$ layer with 98% Al content adjacent to the cavity. This design with a negative gain-mode offset is well suited for high-temperature operation of the array at high bias currents. However, smaller offsets would enhance the modulation response at low temperatures and a lower reflectivity bottom mirror would increase output power. To manage the temperature of the laser, 2 μm of copper was plated around all the device mesas, including on the sidewalls [8]. To improve the bonding process the sample was then plated with indium before being flip-chip bonded on a GaAs heatspreader [9]. Copper plating and flip-chip bonding effectively reduced self-heating issues at elevated bias currents by means of reduction in thermal resistance down to 425 C/W for a single mesa identical to those used as elements in this array.

Experiment: The DC characteristics of the array were extracted using a Keithley 2400 source meter and a silicon photodiode along with an optical attenuator. Fig. 1 presents the array characteristics with a threshold current and voltage of 40 mA and 1.7 V, respectively. The CW output power of the array is above 120 mW at 500 mA bias current and room temperature.

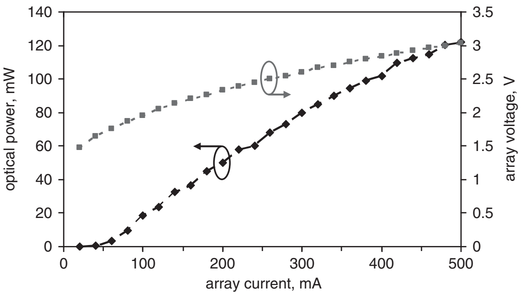

Fig. 1 *L–I–V characteristics of array*

To measure the array's modulation response, it was biased at fixed currents up to the 500 mA maximum current rating of the Cascade Microtech high frequency probe used in this experiment. The output light was coupled into a multimode bare 62.5 μm core diameter fibre. The output signal of a Discovery Semiconductor DS30S *pin* photodiode was then amplified by a Miteq radio-frequency low noise amplifier and an Agilent 8722ET vector network analyser was employed to extract S_{21} parameters of the array at different bias currents. Fig. 2 depicts modulation responses for selected bias currents at 20°C. The array exhibits a 3 dB frequency of 7.5 GHz at a 500 mA bias current. Cutoff frequency of the high current Picosecond Pulse Labs bias tee employed here prevents accurate measurements below 1 GHz. The laser array bandwidth could be extended to higher frequencies by increasing the bias current. Frequency response measurements for a single 18 μm active diameter laser nominally identical to those constituting the array show that a 3 dB modulation frequency of over 11 GHz is achievable. This laser has an output power of 4.9 mW at 20 mA bias current.

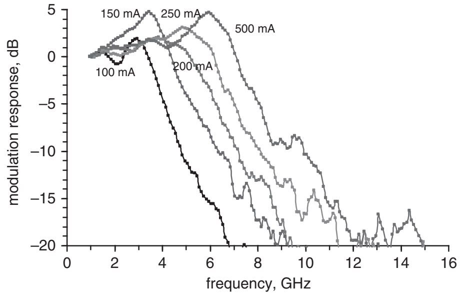

Fig. 2 *Array modulation frequency response for various bias currents*

A bare multimode fibre was employed to scan across the array and measure the frequency response of array elements at different positions. The graded index 62.5 μm core fibre with maximum $N.A = 0.275$ was sequentially positioned above individual array elements in the *x*- and *y*-directions while staying at a fixed ~125 μm distance above the VCSEL surface. Fig. 3 shows that the frequency response of elements of the array at different radii measured from the centre of the array is nearly independent of position. This result indicates that both the individual laser performance and current distribution are relatively uniform over the entire array. Hence, it is anticipated that similar VCSEL arrays may be scaled up to hundreds or thousands of elements to achieve watt level CW powers with modulation frequencies approaching 10 GHz. VCSEL arrays of this type are expected to be useful for a moderate range, high resolution LIDAR and free-space communication.

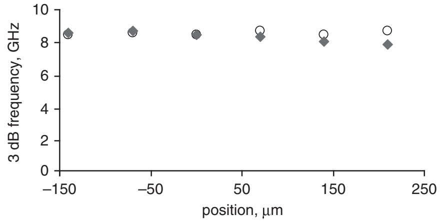

Fig. 3 *Laser modulation frequency for different array positions at 450 mA bias current*

Conclusions: A uniform high-power, high-speed VCSEL array has been demonstrated. Powers of greater than 120 mW with modulation frequencies of >7.5 GHz are achievable with a 28-element array using 18 μm active diameter lasers operating in parallel. Effective heatsinking by metal plating and flip-chip bonding allows CW operation of the array at room temperature. The same approach with an increasing number of single elements can be used to enhance the output power of high-speed VCSEL arrays.

Acknowledgment: This work is supported by the Defense Advanced Research Projects Agency (DARPA) under contract W911NF-08-1-0047.

21 November 2008
doi: 10.1049/el.2009.3353

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