Red microchip VECSEL array

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Abstract: We report an InGaP/AlInGaP/GaAs microchip vertical-external-cavity surface emitting laser operating directly at red wavelengths and demonstrate its potential for array-format operation. Optical pumping with up to 3.3W at 532nm produced a maximum output power of 330mW at 675nm, in a single circularly-symmetric beam with $M^2<2$. Simultaneous pumping with three separate input beams, generated using a diffractive optical element, achieved lasing from three discrete areas of the same chip. Output power of ~95mW per beam was obtained from this 3x1 array, each beam having a Gaussian intensity profile with $M^2<1.2$. In a further development, a spatial light modulator allowed computer control over the orientation and separation of the pump beams, and hence dynamic control over the configuration of the VECSEL array.

OCIS codes: (250.7260) Vertical cavity surface emitting lasers; (140.7300) Visible lasers

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1. Introduction

Vertical external cavity surface-emitting semiconductor lasers (VECSELs) are proving attractive as sources of Watt-power-level visible light for applications including laser projection displays, reprographics and printing, and as specialized sources for scientific and instrumentation applications. We have recently reported direct, high-power red lasing from a VECSEL, demonstrating 0.4W in a TEM_{00} output beam tuneable near 674nm [1]. In that case the laser had a standard 3-mirror cavity and utilized an optically-pumped InGaP/AlInGaP gain structure. Here, based on the same material system, we demonstrate a high-power monolithic version of the device, and explore the generic capability of this format of VECSEL for array-format operation. The device concerned is a so-called "microchip" VECSEL [2,3], where a single-crystal diamond heatspreader, bonded to the gain structure for heat extraction, is dielectric-mirror-coated on its outer surface to form the optical cavity and output coupler. The planar and monolithic nature of the structure offers the opportunity to pump the device with multiple pump beams to obtain a high power laser array where, importantly, the characteristics of each beam are determined separately by the local properties of the semiconductor wafer. We report a demonstration of such capability, operating a 3 x 1 microchip VECSEL array and achieving ~95mW per output beam in the red, each with M^2<1.2. We also show the potential of computer control over the configuration of the VECSEL array, by using a spatial light modulator (SLM) in the pump beam for a simple 2-beam demonstration. Potential applications of this technology include atom optics and chip-based biosystems. For the former, for example, there is much recent interest in obtaining arrays of selectively-addressed dipole traps requiring careful control of beam quality and power per beam at selected wavelengths which include red transitions in lithium atoms [4]. For the latter, versatile multiple beam optical tweezing is possible [5], for example, with characteristics overcoming limitations of electrically-driven VCSEL arrays [6].

2. Experimental set-up and results

The VECSEL structure, as reported and characterized previously [1], was grown by molecular beam epitaxy on a 2" diameter GaAs substrate and consists of an AlGaAs distributed Bragg reflector with a monolithically grown AlInGaP gain region. The gain region has AlInGaP pump-absorbing barriers and 20 compressively strained InGaP quantum wells for emission at ~670nm. A 4x4mm^2 sample was cleaved from the VECSEL wafer and bonded to a 4x4mm^2, 250µm-thick single-crystal diamond platelet, using the method of liquid capillary bonding reported earlier [7]. The diamond had a dielectric coating for high transmission at the pump wavelength and 99% reflectivity at the laser wavelength, and therefore had a dual purpose of acting as (a) an intracavity heatspreader for surface cooling of the VECSEL wafer and (b) as the laser cavity output coupler. The microchip VECSEL was clamped in a water-cooled brass mount with a layer of 125µm-thick indium foil between the substrate and brass. Optical pumping was performed through a 3mm-diameter aperture in the top plate of the mount.

Before arranging the pump optics for array format operation, the VECSEL microchip was pumped with up to 3.3W at 532nm through a 100mm focal length singlet lens producing a (measured) single 30µm diameter focus spot. With the water to the brass mount maintained at -5°C, a maximum output power of 330mW was achieved in a near-Gaussian beam (see inset, Fig. 1(a)). The power transfer shows a threshold of 1.2W and a slope efficiency of 31% just above threshold which reduces to 18% at input powers above ~1.6W as the VECSEL cavity mode changes. The beam propagation ratio (M^2) was measured to be less than 2 at high power. The output spectrum of the laser (measured with spectrometer resolution ~0.3nm), shown in Fig. 1(b), was ~4nm broad, and centred on 676nm with a modulation corresponding to the free spectral range of the diamond cavity.

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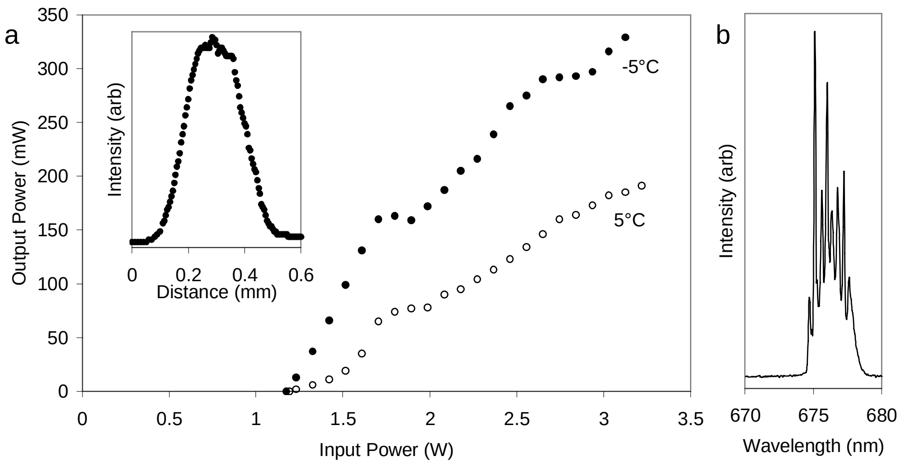

Fig. 1. (a) Power transfer of the microchip VECSEL for mount temperatures of -5°C and 5°C, respectively. Inset: Far-field profile of the output beam. (b) Output spectrum of the microchip VECSEL at high power.

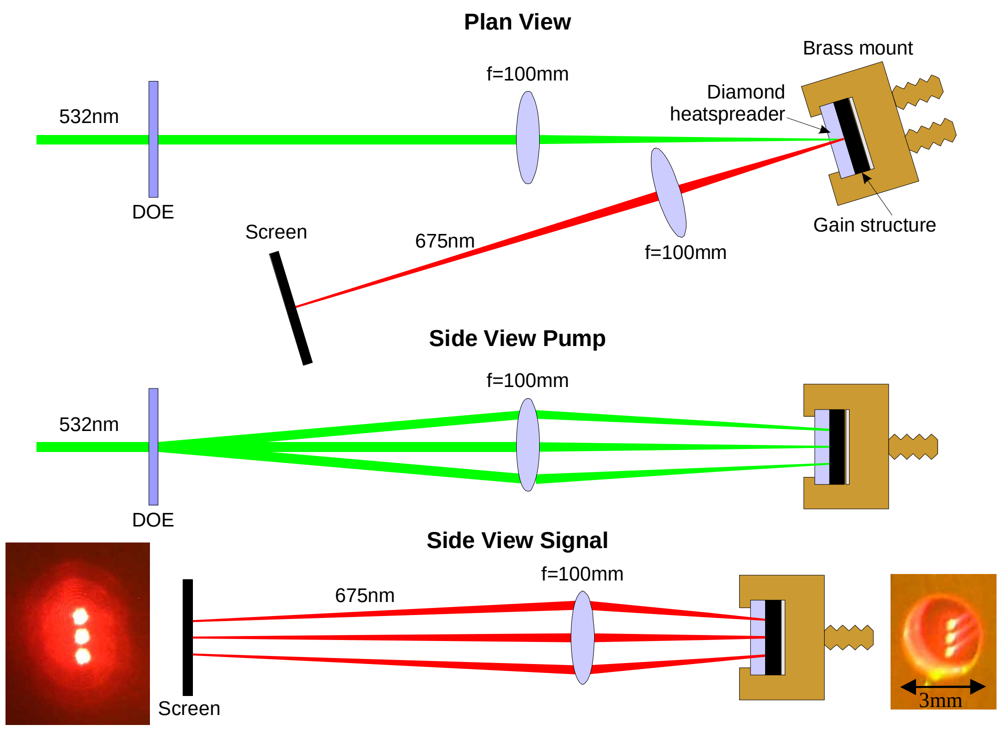

Fig. 2. Schematic diagram of the 3 x 1 VECSEL array set-up, showing the plan view and the side view of the pump and signal beams. Inset: photographs of the lasing microchip wafer (right) and the output beams on the screen (left).

The experimental set-up for the 3x1 microchip VECSEL array is shown in Fig. 2. The pump beam was split into three identical beams with an appropriate diffractive optic element (DOE) placed before the pump focusing lens. The beams were diverging from the DOE which allowed the single pump lens to bring all three to separate and near-identical foci on the VECSEL wafer. The centre-to-centre separation between adjacent foci at the VECSEL was 0.5mm and the size of each focus was measured to be 30µm in diameter, demonstrating that the DOE had no obvious effect on the initial pump beam characteristics other than providing

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an equal division of power. A second identical lens was used to image the output beams from the VECSEL chip onto a detector or viewing screen.

A 5μm-wide horizontal slit was moved vertically through the image of the array and the transmitted power was noted at 10μm intervals. The resulting transverse spatial profiles of each beam are shown in Fig. 3(a). Each beam had a Gaussian profile, of equal size and approximately equal power. The beam propagation ratio (M^2) was measured to be less than 1.2 at high power for each of the three. The power transfer for each beam, shown in Fig. 3(b), was measured with the brass mount cooling water at 5°C, and is plotted with respect to the measured input power from a single pump beam, i.e. ~1/3 of the total pump power passing through the DOE. The threshold of each laser was ~0.6W, with an average slope efficiency of 14%. The maximum output power from the top, middle and bottom lasers was 97mW, 94mW and 91mW, respectively. At room temperature, this fell to an average of 60mW.

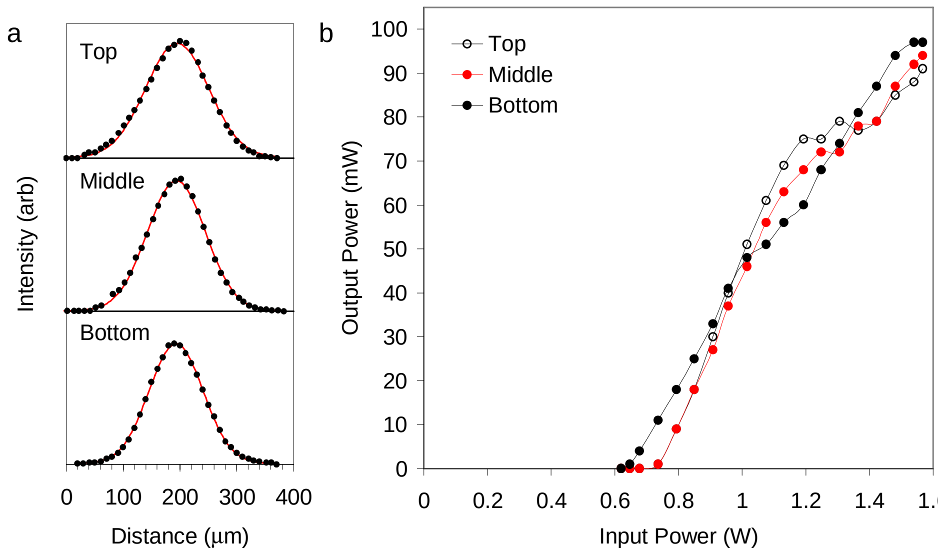

Fig. 3. (a) Measured profile of each output beam with a Gaussian fit to the data points. (b) Power transfer of each beam.

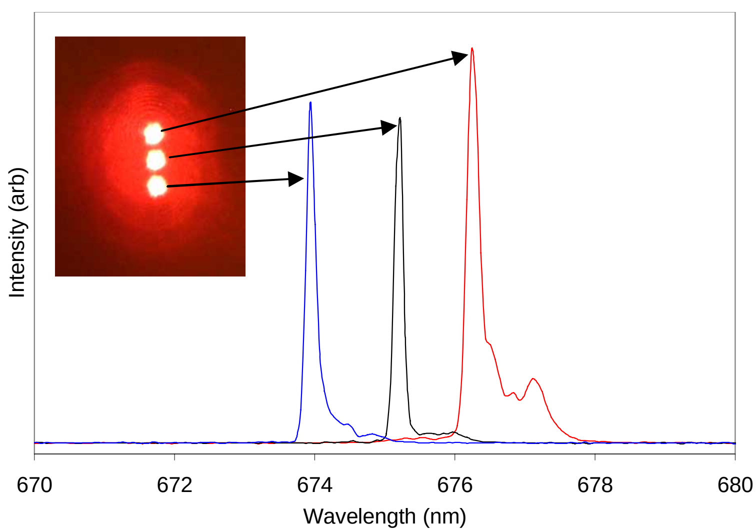

Fig. 4. Output spectrum of each beam. The peak wavelengths of the spectra for the top, middle and bottom output beams are 676.2nm, 675.2nm and 674nm, respectively.

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The output spectra of the array are shown in Fig. 4. In contrast to the single beam VECSEL, at the lower input power per beam of the array, only one peak in the broad modulated gain spectrum can in general oscillate. Different areas on the non-uniform VECSEL wafer have different peak wavelengths. The peak wavelengths of the spectra for the top, middle and bottom output beams are 676.2nm, 675.2nm and 674nm, respectively. These spectra are representative, and we note that different positioning of the pump beams give different spectra within the range 673-678nm. With appropriate control of gain wafer characteristics, these beams could be made to be nominally identical, or the centre wavelengths and separation controlled deliberately, for example through direct methods of control such as quantum well intermixing [8].

The output beams were collimated and passed through a broadband polarizing beamsplitter cube and the transmitted power was measured with the rotation of the cube to determine the polarization. All three beams were found to be linearly polarized with the same orientation and a measured extinction ratio of >300:1 (the cube extinction ratio). As noted in our previous work with the conventional three-mirror VECSEL, the polarization was orientated parallel to the major (0,-1,-1) flat axis in the plane of the crystal.

Figure 5 shows the experimental set-up for computer control of the VECSEL array configuration. The 3mm-diameter collimated pump beam was expanded to ~12mm and reflected off a computer-controlled spatial light modulator (SLM) based on a Hamamatsu PAL-SLM X7665. The SLM is an optically addressed, nematic liquid crystal with VGA resolution, with diffraction efficiency in the region of 30% and near video update rate. The efficiency of the SLM is strongly dependent on the polarization of the incident light; hence a half-wave quartz retarder was used to rotate the polarization of the pump beam. Once again, a single lens was used to focus the modulated pump beam onto the microchip VECSEL, this time with a longer focal length of 500mm to achieve a similar size of pump focus (26μm) to the previous array, with the expanded collimated pump beam.

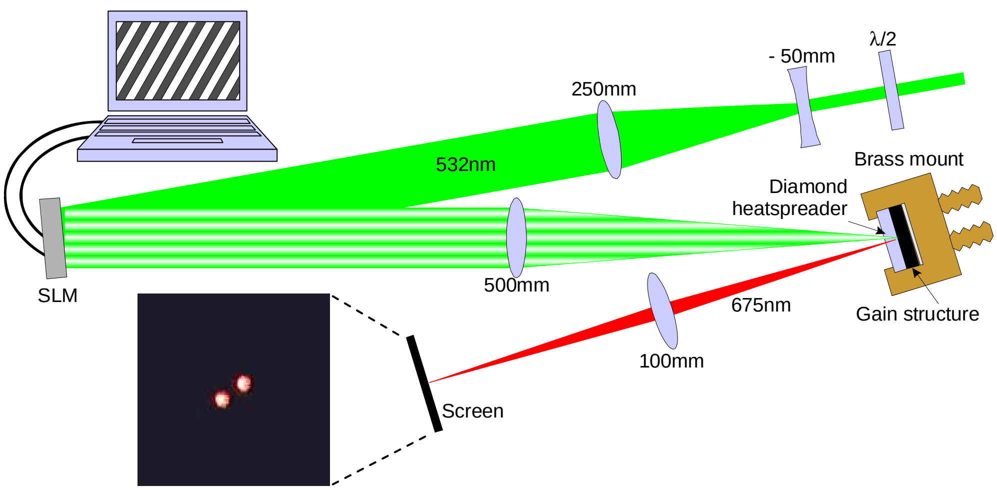

Fig. 5. Experimental set-up for controlling the VECSEL array with a spatial light modulator (SLM). Inset: (1.56 MB) movie of the rotating VECSEL beams

The diffraction pattern produced by the SLM in the Fourier-plane with respect to the microchip VECSEL, resulted in a zero order beam and a first order diffracted beam. Due to the low diffraction efficiency of the SLM, the greater part of the 2W maximum incident power (~900mW) appears in the zero order leaving ~600mW in the second beam. In a simple demonstration, a computer program was written to produce a rotating diffraction pattern on the SLM so that the first order beam rotated about the zero order beam, which in turn led to one VECSEL laser orbiting another, as shown in Fig. 5. The computer program used a modified Gerchberg-Saxton algorithm, as described in [9].

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5. Conclusions

A microchip VECSEL based on the AlInGaP material system has been shown to provide high power CW operation at 676nm. Up to 320mW output was achieved in a good quality single output beam. The monolithic nature of the device was shown to facilitate array operation, with potential implications for a range of fields including atom optics and biochips. By passing the pump beam through a diffractive optic element, the VECSEL chip was simultaneously pumped with three discrete beams to achieve lasing from three separate and discrete areas of the same device. All three beams had similar characteristics including high power (~95mW), low beam propagation ratio ($M^2<1.2$) and linear polarisation. The three lasers extract their gain from different areas of the non-uniform VECSEL wafer and therefore had different peak output wavelengths, a feature which could be controlled, in principle, by the epitaxy, post-processing and/or the spatial separation of the pump beams on the chip. Computer control over the VECSEL array configuration was achieved with the use of an optically-addressed spatial light modulator to modulate the pump beam. In a simple demonstration this allowed one VECSEL output beam to rotate about another. With sufficient pump power and/or optimising threshold and slope efficiency, this result should readily be scalable to larger 2-dimensional arrays of high power lasers from a single semiconductor chip. In addition, coherent coupling between the beams should be possible in some formats.

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