Coherently Coupled Photonic-Crystal Surface-Emitting Laser Array


Abstract—The realization of a $1 \times 2$ coherently coupled photonic crystal surface emitting laser array is reported. New routes to power scaling are discussed and the electronic control of coherence is demonstrated.

Index Terms—Photonic-crystal surface-emitting laser array (PCSEL).

I. INTRODUCTION

There has been considerable recent interest in photonic crystal surface emitting lasers (PCSELs) due to the demonstration of vertical single mode emission over a large area [1]–[5]. These devices have been shown to give high power that scales with area, low divergence [3], [4], control of beam shape and polarisation [6], [7], and beam steering [8]. Realisation of PCSEL's is normally through wafer fusion [9] or by epitaxial regrowth of voids [1]. There has also been considerable work on all-semiconductor PCSELs whereby epitaxial regrowth is used to fully fill etched holes and leave a photonic crystal PC which is all-semiconductor [10]–[12].

Williams et al. demonstrated single mode emission from an all semiconductor PCSEL [10], and showed a higher mode overlap with the PC region than their void containing counterparts [11]. Fig. 1(a) shows a schematic diagram of the PCSELs considered in this paper where the photonic crystal and active layers are located between p- and n- cladding layers, providing in-plane optical wave-guiding. A schematic of a photonic crystal unit cell is shown in Fig. 1(b), where we define A to be the atom shape and material, with B the background material, r is atom radius and a is photonic crystal period. Fig. 1(c) shows a schematic of the layer structure of the PCSEL considered in this paper. There has been considerable effort to model the effect of atom shape on the performance of the PCSEL, where the engineering of the in-plane electric field allows control of the far-field power, beam shape and polarization [13]. PCSEL arrays have demonstrated powers as high as 35 W [14] but the devices in these arrays have not demonstrated coherence or that coherence can be controlled.

In this paper we demonstrate that we are able to realize an array of 4 all-semiconductor PCSELs which may be operated CW with $<1^\circ$ divergence (diffraction limited), and essentially identical threshold current densities and emission wavelength. Developments in fabrication and regrowth technologies have allowed a significant improvement over our previous work [10], [12].

We then go on to realise a $1 \times 2$ coherently coupled PCSEL array, controlled by contacted connecting waveguides (“couplers”). These couplers can be operated in loss, transparency or...
gain through a small change in the injected current. We show new opportunities in power scaling through the coupling of adjacent PCSELs and evidence for injection locking between the PCSELs. Finally we demonstrate the electronic control of coherence between PCSEL elements of the array by changing the current applied to the coupler sections. In addition to demonstrating that the array elements are coherent with each other, we demonstrate that this shows for the first time that the individual PCSELs emit coherently across their surface.

II. PCSEL FABRICATION AND REALISATION

In this section we describe device growth and fabrication and show the characteristics of individual PCSELs. Initial growth occurred on a GaAs substrate, 3° off toward (110), consisting of: 1.5 μm of n-Al0.4Ga0.6As, three 8 nm In0.2Ga0.8As quantum wells with 20 nm GaAs barriers, a 40 nm p-In0.48Ga0.52P etch stop layer and a 20 nm p-GaAs buffer layer. Above this is was a 150 nm of p-In0.48Ga0.52P and a 20 nm p-GaAs terminating layer. Electron beam lithography and reactive ion etching was utilised to transfer a square lattice, circular dielectric cylinder photonic crystal pattern into a SiO2 hard mask. This pattern was transferred into the InGaP layer by an CH3/He/O2 reactive ion etch. The hard mask was then removed and regrowth to fill the PC structure, planarise the waveguide, and grow upper p-doped cladding layers was undertaken in a MOVPE reactor. Prior to device fabrication, the MOVPE process was optimized due to the high aspect ratio of the PC features [10]–[12].

The regrowth procedure involves the patterned wafer being etched in buffered HF for 30 s prior to being loaded into the growth reactor. There is a trade off in the choice of regrowth temperature. High temperatures are required to desorb natural oxides, yet result in As:P exchange, which we aim to minimise. Low temperatures lead to the formation of threading dislocations. These constraints on growth temperature remove an element of freedom when trying to ensure good planarization during the regrowth process. In order to optimise the regrowth process, samples identical to the final PCSEL design were realised which differed by having a PC layer (p-In0.48Ga0.52P) of 150 nm in thickness. Following regrowth, devices were formed by etching a 400 nm deep 100 μm diameter mesa in the p+GaAs contact layer above the centre of the photonic crystal. An annular gold contact was defined, providing a 52 μm aperture for light extraction. The electrically driven region (100 μm diameter plus current spreading) is smaller than the regrown photonic crystal area (150 μm × 150 μm).

Fig. 2 shows the CW electroluminescence (EL) spectra of a typical all-semiconductor PCSEL operating at room temperature at 100 mA showing emission at 991 nm, the inset is zoomed in on the same spectra, showing that the full-width at half-maximum (FWHM) is 0.5 nm.

Fig. 3 shows the CW light output-current (LI) curve of a typical PCSEL operating at room temperature showing the threshold current of the device to be 65 mA, the inset shows the far field pattern of the same device operating well above threshold. 52 μm diameter aperture. This shows the first demonstration of an all-semiconductor PCSEL operating continuous wave at room temperature and shows a lower divergence than our previously realized devices.

The threshold current ($I_{th}$) of the device is 65 mA, which gives a threshold current density ($J_{th}$) of ~8 kA/cm². Previously studied all semiconductor PCSELs in Williams et al., had a $J_{th}$ of ~100 kA/cm². The output power at 100 mA was ~10 kW, giving a slope efficiency of 3.3 μW/mA. This is a significant reduction in the $J_{th}$ and can be attributed to a number of possible differences between the two devices. Firstly, these devices have an atom radius of 0.4a (compared to ~0.2) which is shown in Taylor et al. [15] to give a high coupling coefficient, reducing threshold gain. However, this enhanced coupling will also increase out-of-plane scattering that acts as an internal loss prior to lasing. An improvement in sidewall verticality in the present structures is expected to reduce parasitic out-of-plane scattering. Secondly the cleaning process before regrowth was improved, and is likely to give the main enhancement of threshold current density, finally the MOVPE regrowth process has been improved.

III. COUPLED ARRAY

In this section we characterise the PCSEL array. The array consists of four PCSELs (as describe in Section I) in a 2 × 2 array separated by 1 mm, shown schematically in Fig. 4. The cou-
Fig. 4. Schematic of a $1 \times 2$ PCSEL array.

Fig. 5. Spectra of four neighboring devices on the same coupled device with each device operated at 100 mA CW at room temperature.

Fig. 6. Light output-current curve of four neighboring PCSELs from the same $1 \times 2$ array.

Fig. 7. Power as a function of current for PCSEL$_A$ with PCSEL$_B$ kept below threshold and the coupler in loss (red dashed) and in gain (black solid), inset shows a schematic of the array indicating how experiment was setup.

In the following we refer to a number of experiments where we refer to the coupler section being in gain or loss. Length characterization of as-cleaved lasers with the same contact method and width as the coupler indicate a transparency current density of $\sim 220 \pm 4$ A cm$^{-2}$. We experimentally determined two current levels at which we observed evidence for coherent coupling and injection locking which we refer to as the coupler being in gain ($220$ A cm$^{-2}$), and a current level at which we could not observe such effects, which we refer to as the coupler being in loss ($200$ A cm$^{-2}$).

Fig. 7 shows output power of PCSEL$_A$ as a function of current for a $1 \times 2$ PCSEL array where PCSEL$_B$ is driven sub-threshold ($I_B = 60$ mA, $I_{\text{thresh}} = 68$ mA) at, or close to, transparency. The PCSEL$_A$ current is varied from 60 mA to 80 mA with the coupler in gain (black) or loss (red). This is shown schematically in the inset. With the coupler in loss the curve shows the lasing threshold of a single PCSEL with a threshold of 65 mA. Reducing the coupler current further did not significantly affect the results. With the coupler in gain the same threshold can be observed but the slope efficiency is increased. We attribute this increase in slope efficiency to light travelling in-plane, exciting PCSEL$_A$ being amplified along the coupler, subsequently reflected from PCSEL$_B$ once more amplified along the coupler, and subsequently contributing to an increased lasing power.
from PCSEL\textsubscript{A}. Current leaking from the coupler into PCSEL\textsubscript{A} may result in a reduction in threshold but cannot explain their increased slope efficiency observed here. Similarly, additional light generated by the coupler being injected into the PCSEL cannot explain the increased slope efficiency.

Fig. 8 shows output power of PCSEL\textsubscript{A} as a function of current for a 1\times2 PCSEL array where PCSEL\textsubscript{A} is driven sub-threshold ($I_{A} = 60 \text{ mA}$, $I_{\text{Thresh}} = 65 \text{ mA}$) at, or close to, transparency. The PCSEL\textsubscript{B} current is varied from 60 to 80 mA with the coupler in gain (black) or loss (red). This is again shown schematically in the inset. With the coupler in loss, the output power of PCSEL\textsubscript{A} is independent of the current applied to PCSEL\textsubscript{B}, demonstrating that in this case the two PCSELs are optically, electrically, and thermally isolated. With the coupler in gain the power emitted from the PCSEL\textsubscript{A} device significantly increases for PCSEL\textsubscript{B} currents greater than 68 mA and rolls over for currents greater than 75 mA. The onset of the increase in power occurs at the threshold current of PCSEL\textsubscript{B}. Due to the equivalence of threshold currents, this behaviour is attributed to waveguided laser emission from PCSEL\textsubscript{B} being out-coupled by the grating in PCSEL\textsubscript{A}. This increase in emission power from an observed PCSEL offers a route to power scaling. The apparent thermal roll-over is attributed to self heating of PCSEL\textsubscript{B} resulting in detuning of the PCSEL\textsubscript{B} emission from the scattering wavelength of the grating PCSEL\textsubscript{A}.

Fig. 9(a) shows the results of EL spectral measurements of the 1\times2 PCSEL array where PCSEL\textsubscript{B} is lasing (80 mA), the coupler is in loss and the current in PCSEL\textsubscript{A} is varied from 60 to 80 mA. The inset shows a schematic of this condition, similar to that in Fig. 7, but now with PCSEL\textsubscript{B} lasing. As the two PCSELs are optically isolated (confirmed by reducing the coupler current to even lower levels), these spectra show the spectral behaviour of the un-coupled PCSEL\textsubscript{A}. Fig. 9(b) shows the same measurement, but with the coupler in gain. At PCSEL\textsubscript{A} currents below threshold, the spectra show emission attributed to out-coupling of PCSEL\textsubscript{B} emission via the PC in PCSEL\textsubscript{A}. A higher intensity of emission is observed when PCSEL\textsubscript{A} reached threshold.

Fig. 10(a) and (see Fig. 10(b)) plots the peak wavelength as a function of applied current extracted from Fig 9(a) (see Fig. 9(b)). For Fig. 10(a) the peak wavelength monotonously increases from 991.20 nm to 991.43 nm over a current range from 66 to 80 nm, giving a peak shift of 0.016 nm/mA. As we are observing an isolated PCSEL, this shift is attributed to the self-heating of the device. From previous work [5], this indicates a $\sim 6–7 \degree C$ increase in junction temperature.

While Fig. 10(b) shows the same experiment, but now with the coupler in gain. For the same range of currents applied to PCSEL\textsubscript{A} the peak wavelength remains constant at 991.30$\pm 0.03$ nm. In this case, the self-heating induced shift of the lasing wavelength of PCSEL\textsubscript{A} is not observed. We attribute this to PCSEL\textsubscript{A} now being injection locked to PCSEL\textsubscript{B} [16], [17], the injection locking occurs through the transparent coupler.

Fig. 11 shows the EL spectra from PCSEL\textsubscript{A} in the same 1\times2 PCSEL array where the current in PCSEL\textsubscript{A} is held constant 80 mA, the coupler is in gain, and the PCSEL\textsubscript{B} current is varied from 60 to 80 mA. At currents below the lasing threshold of PCSEL\textsubscript{B} laser emission from PCSEL\textsubscript{A} is observed. As PCSEL\textsubscript{B} current is increased, total output power is increased, and at the highest PCSEL\textsubscript{B} currents a reduction in peak lasing wavelength is observed.

Fig. 12 shows the peak wavelength extracted from Fig. 11. A reduction in PCSEL\textsubscript{A} peak lasing wavelength is observed.
when PCSEL_B reaches threshold. This is again attributed to the injection locking of the two PCSELS.

IV. ELECTRONIC CONTROL OF COHERENCE

In this section we use the coupled array to electronically control the coherence of adjacent devices by the control of current applied to the coupler region. In order to ensure that the phase matching condition is met regardless of coupler current, we designed the coupler length to be 1 mm. This gives a Fabry–Pérot (FP) mode spacing of 0.13 nm, meaning that the phase matching condition is met for a hand-full of F-P modes within the lasing line-width.

Fig. 13 shows a schematic of the experimental setup used to show (or show the absence of) coherence of adjacent PCSELS. The left hand image schematically shows the near field image of a PCSEL array magnified onto a camera. The right hand image shows how the insertion of a mirror reflects the near-field image of one PCSEL so that it overlays the image of its neighbouring PCSEL. The observation of an interference pattern will therefore provide evidence of coherence between the PCSELS.

Fig. 14 shows results from this experiment. The top left image shows the case where both devices are sub-threshold and the coupler is in loss. This shows a low intensity image with no evidence for an interference pattern, demonstrating that the devices are incoherent. The top right image shows the case where both devices are subthreshold and the coupler is in gain. For this case there are still no fringes but the intensity is increased. This is attributed to aditional spontaneous emission from the coupler being out-coupled by the two PCSELS.

The bottom left image shows the case where both devices are lasing (80 mA) and the coupler is in loss. This shows a further increase in intensity again (due to lasing), but no interference pattern is observed indicating that even though the devices are lasing, they are mutually incoherent. The bottom right image shows the case where both devices are lasing and the coupler is in gain. A clear interference pattern is observed. The calculated fringe spacing for our experimental set-up is $36 \pm 4 \mu m$, the
measured spacing $36.6 \pm 5 \, \mu m$, which are in excellent agreement. In addition, the observation of such an interference pattern demonstrates coherence over the entire surface of the individual PCSELs. This demonstration of mutual coherence of the two PCSELs, allows the realization of the Young’s double-slit experiment in the solid state.

V. SUMMARY

We have demonstrated a $1 \times 2$ array of all-semiconductor PCSELs which may be operated CW with $<1^\circ$ divergence (diffraction limited), and essentially identical threshold current densities and emission wavelength. We subsequently realised a $1 \times 2$ coherently coupled PCSEL array, controlled by contacted connecting coupler waveguides. We have shown new opportunities in power scaling through the coupling of adjacent PCSELs and shown spectroscopic evidence for injection locking between the PCSELs. Finally, we demonstrated the electronic control of coherence between PCSEL elements of the array by changing the current applied to the coupler sections.

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REFERENCES


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