Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp291-292

Power Scaling in Photonic Crystal Surface Emitting Laser Arrays

Ben C. King[1*], Katherine J. Rae[1], Adam F. McKenzie[1,2], Aleksandr Boldin[1], Daehyun Kim[1], Neil D. Gerrard[1], Guangrui Li[1], Kenichi Nishi[3], Keizo Takemasa[3], Mitsuru Sugawara[3], Richard J.E. Taylor[1], David T.D. Childs[1], Richard A. Hogg[1]
[1]James Watt School of Engineering, University of Glasgow, UK
[2]CST Global Ltd., UK
[3]QD Laser Inc., Japan
*b.king.1@research.gla.ac.uk

Abstract

We describe power scaling in photonic crystal surface emitting laser arrays and demonstrate how such arrays lead to increased efficiency in a three-element array due to a reduction of in-plane loss of optical power.

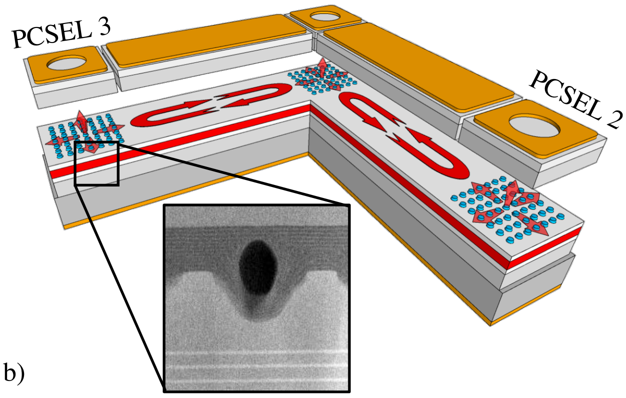
I. Introduction

Photonic crystal surface emitting lasers (PCSELs) are a new class of semiconductor laser which incorporate a 2D photonic crystal (PC) layer into a semiconductor laser structure. They offer the possibility high power single mode surface emitting laser with narrow divergence[1], and through design of the photonic crystal (PC) region ultimate control over wavelength, polarization[2], and beam shape of emission[3]. Unlike vertical cavity surface emitting lasers, PCSELs allow for large single-mode powers through scaling the emission area. Allowing for the realization of high brightness laser diodes[4]. However, there are practical limits to the size and power of a single device, relating to self-heating, difficulties in achieving uniform carrier distributions, optical loss in current spreading layers, and maintaining single mode emission. Coherently coupled PCSEL arrays are the next logical step in achieving high PCSEL power and further improvements to brightness[5], [6]. We demonstrate power scaling in a three PCSEL array, showing how improved efficiencies can be achieved through recycling of in-plane loss.

II. Methods

The PCSEL array considered in this paper is shown in fig.1 a). Each individual PCSEL device consists of a 2D PC of circular holes in a square lattice, etched into a GaAs layer directly above GaAs/InGaAs MQWs. This wafer is then regrown in one step, infilling the holes with an AlAs/GaAs superlattice. Fig. 1 a) shows a cross sectional TEM of the PC region after regrowth, demonstrating how growth has given rise to voids within the PC holes. Each PCSEL devices is 150um x 150um, and each PCSEL is connected by a 150um x 1000um coupler region. The coupler regions are the same structure as the PCSELs, but without the PC patterning. This allows for these regions to electrically pumped to transparency in order to control the interaction of adjacent devices. The individual PCSELs will hence be able to communicate with each other through the light emitted perpendicularly at the edges of the devices, known to be large in our symmetrical circular PC design[7], and achieve in-plane coupling. The devices were pumped using a multichannel pulsed current source, custom built for the purpose of delivering synchronous pulses to the PCSEL and coupler regions, using a 1% duty cycle and 2us pulse width.

a)



b)

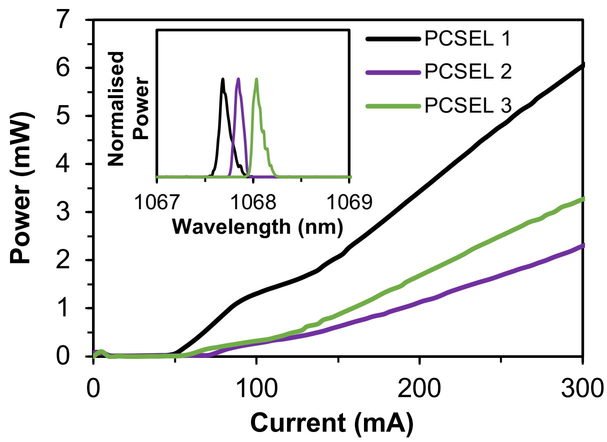


Figure 1. a) Schematic of PCSEL array and TEM showing details of the PC structure, and **b)** L-I characteristics of the PCSELs operated individually.

III. Results

Fig. 1 b) is a plot of the LI characteristics of each of the individual PCSEL devices (i.e. no current applied to the coupler contacts). Inset are spectra from each individual device at 150ma. The three devices show very similar behavior, and have a comparatively low output power due to the symmetric PC structure used, loss of ~half the output to the substrate, and coverage of the PCSEL by the contacts. Lasing wavelengths are observed to be within 0.5nm of each other.

Fig.2 a) considers two PCSEL devices and their connecting coupler region. The line plot is a plot of the total power of the light emitted perpendicularly from the system, as the current to each coupler region is concurrently varied. It can be seen that when there is no current supplied to the PCSELs (blue) there is little emission from the system until the system begins to lase at ~250mA. When the PCSELs are held at 300ma (red)

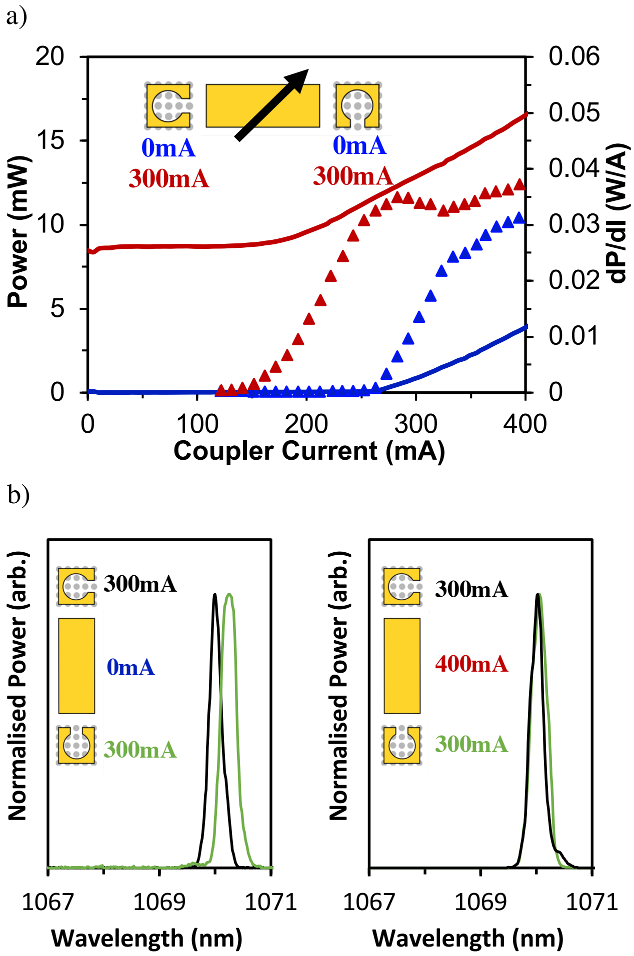


Figure 2. a) Line plots show the power of light emitted from two PCSEL devices for varying current supplied to coupler region. Blue is with no current being supplied to the PCSEL devices and red is with 300mA supplied to each device. Scatter pot is of the dP/dI of each power plot. **b)** Spectra of individual PCSELs at 300mA with no current and 400mA in the coupler region.

the initial power is the sum of the power from each PCSEL at 300ma. As coupler current is increased, there appears to be a soft turn-on at ~150mA. This is attributed to the increasing transparency of the coupler regions with increasing current. Characterisation of the device suggests a transparency current for the coupler of 235mA. For two PCSELs connected by transparent couplers, a 25% increase in output power is observed (8.46 mW c.f. 10.63 mW), and there is an increase of differential efficiency from 0.02 W/A for the two PCSEL elements on their own to 0.026 W/A for the array. Fig. 2 b) shows that when there is sufficient current applied to the coupler, there is a locking of the individual PCSEL wavelengths, to within the bandwidth resolution of our measuring system. This suggests that the devices in our arrays are coherently locking.

For a system of three connected PCSELs, the total power increase at coupler transparency increases to 36%, as shown in fig. 3. The differential efficiency of the system is 0.026 W/A at the transparency point for the couplers, compared to 0.019 as the average for three independent PCSEL elements.

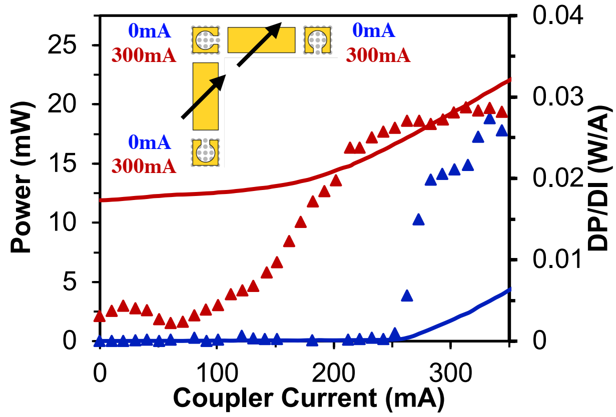


Figure 3. Line plots show the power of light emitted from all PCSEL devices for varying current supplied to each coupler region. Blue is with no current being supplied to the PCSEL devices and red is with 300ma supplied to each device. Scatter pot is of the dP/dI of each power plot.

A maximal differential efficiency of 0.028 W/A is observed at ~350 mA.

At the conference, we will discuss further the power and efficiency benefits of using PCSEL arrays, compare these benefits to increasing the size of a single device using device simulation, and extrapolate our results to talk about the possibilities of full 2D PCSEL arrays.

Acknowledgements

This work was supported by the Engineering and Physical Sciences Research Council (RCUK Grant No. EP/L015323/1).

References

[1] M. Imada, S. Noda, A. Chutinan, M. Murata, and G. Sasaki, “Semiconductor lasers with one- and two-dimensional air/semiconductor gratings embedded by wafer fusion technique,” *IEEE J. Sel. Top. Quantum Electron.*, vol. 5, no. 3, pp. 658–663, 1999.

[2] M. Imada, A. Chutinan, S. Noda, and M. Mochizuki, “Multidirectionally distributed feedback photonic crystal lasers,” *Phys. Rev. B*, vol. 65, no. 19, pp. 1–8, 2002.

[3] E. Miyai, K. Sakai, T. Okano, W. Kunishi, D. Ohnishi, and S. Noda, “Linearly-polarized single-lobed beam in a surface-emitting photonic-crystal laser,” *Appl. Phys. Express*, vol. 1, no. 6, pp. 0620021–0620023, 2008.

[4] M. Yoshida *et al.*, “Double-lattice photonic-crystal resonators enabling high-brightness semiconductor lasers with symmetric narrow-divergence beams,” *Nat. Mater.*, vol. 18, no. 2, pp. 121–128, 2019.

[5] R. J. E. Taylor *et al.*, “Coherently Coupled Photonic-Crystal Surface-Emitting Laser Array,” *IEEE J. Sel. Top. Quantum Electron.*, vol. 21, no. 6, pp. 493–499, 2015.

[6] R. J. E. Taylor *et al.*, “Electronic control of coherence in a two-dimensional array of photonic crystal surface emitting lasers,” *Sci. Rep.*, vol. 5, no. 1, p. 13203, Oct. 2015.

[7] A. A. Erchak *et al.*, “Enhanced coupling to vertical radiation using a two-dimensional photonic crystal in a semiconductor light-emitting diode,” *Appl. Phys. Lett.*, vol. 78, no. 5, pp. 563–565, 2001.