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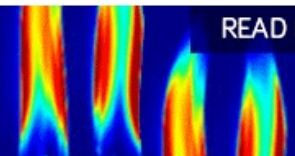
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ABSTRACT

A key benefit of photonic crystal surface emitting lasers (PCSELs) is the ability to increase output power through scaling the emission area while maintaining high quality single mode emission, allowing them to close the brightness gap which exists between semiconductor lasers and gas and fiber lasers. However, there are practical limits to the size, and hence power, of an individual PCSEL device, and there are trade-offs between single-mode stability and parasitic in-plane losses with increasing device size. In this paper, we discuss 2D coherent arrays as an approach to area and coherent power scaling of PCSELs. We demonstrate in two and three element PCSEL arrays an increase in the differential efficiency of the system due to a reduction in in-plane loss.

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INTRODUCTION

Photonic crystal surface emitting lasers (PCSELs) are a new class of laser diodes which incorporate a 2D photonic crystal (PC) layer into a semiconductor laser structure. They offer high power single mode surface emission with narrow divergence¹ and control over wavelength, polarization,² emission beam shape,³ and on-chip beam-steering.⁴ PCSELs allow large single-mode powers through scaling the emission area.⁵

For a PCSEL, the group velocity of light becomes zero at the band-edge which results in the formation of large and stable two-dimensional single-cavity modes. At these lasing points, waves propagating in certain directions couple, increasing the mode density. Wave coupling is possible according to the Bragg condition, resulting in vertical emission, orthogonal coupling, and 1D scattering (reflection). [Figure 1\(a\)](#) shows a schematic of a PCSEL, highlighting the key optical loss mechanisms: α_i (internal loss), α_{\perp} (the out-of-plane emission analogous to the mirror loss in a Fabry–Perot laser), and α_{\parallel} (parasitic loss associated with in-plane loss of optical power).⁵

The value of α_{\parallel} increases exponentially with reducing PC atom number and may be so significant as to make lasing impossible to achieve in small devices^{7,8} unless the light is confined in-plane,⁹ see the [supplementary material S1](#). It is clear that for an ideal PCSEL, α_i and α_{\parallel} are minimized, and α_{\perp} is optimized, e.g., high differential output powers and modest threshold gain values to reduce thermal issues within the laser. A simple strategy is to make the PCSEL as large as possible to reduce α_{\parallel} , but there is a practical limit to such scaling. These limits include non-uniform temperature profiles across the device, high cavity temperatures due to self-heating, difficulties in achieving uniform carrier distributions, optical loss and thermal lensing in current spreading layers, and limitations of the scale of e-beam lithography write-fields before stitching errors are introduced. Current strategies to increase single mode power are to “flatten the mode” by PC design to reduce 1D scattering.⁶ This in turn results in increased loss of power in-plane that is currently ameliorated by making PCSELs of a very large area. Here, we describe coherent PCSEL array power scaling (See [Fig. 1](#)) where higher differential efficiencies are demonstrated as the array number

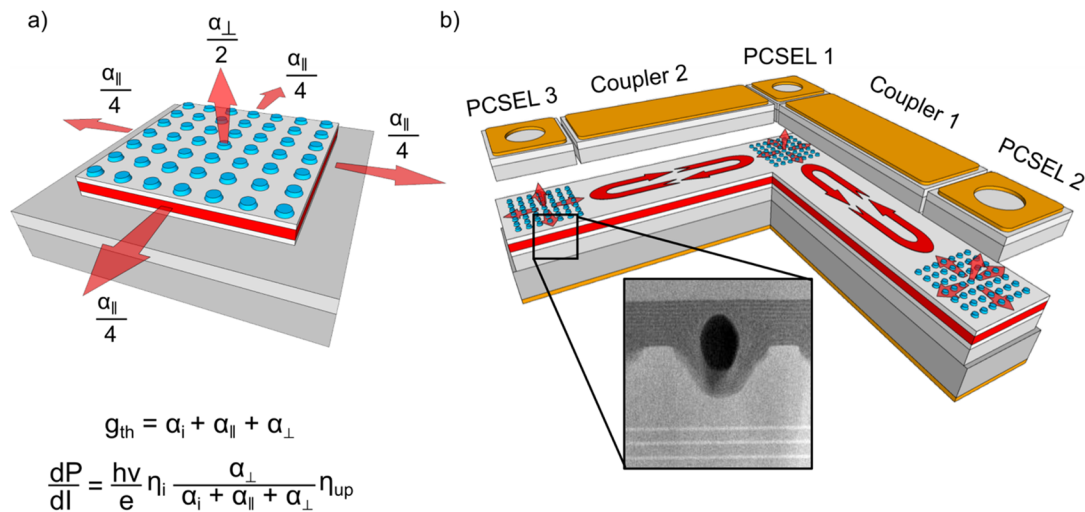


FIG. 1. (a) Schematic of loss mechanisms in PCSELS and (b) the schematic of the PCSEL array considered in this paper, where three PCSEL devices are connected by contacted coupling waveguides. Inset: the TEM image of the PC region of a regrown PCSEL.

increases due to reduced α_{\parallel} . In this approach, individual PCSELS may be optimized (for e.g., single-mode stability, power per unit area, etc.) with area scaling (and brightness enhancement) achieved through coherent coupling of the array, *reducing* the parasitic losses.

A schematic of the PCSEL devices considered in this paper is shown in Fig. 1(b). A PC slab is etched into the GaAs region of a GaAs/InGaAs MQW base wafer and subsequently re-grown so as to create a void within the semiconductor matrix, as shown in the cross-sectional TEM of Fig. 1(b). Details of the fabrication process are described in the Methods section. The voids provide a high coupling strength in the PCSEL due to the large index contrast between the air and semiconductor, albeit with a reduced mode overlap with the PC as compared to all-semiconductor counterparts.^{10,11} Each PCSEL element is $150 \times 150 \mu\text{m}^2$ (480×480 periods), and each PCSEL element is connected by a $150 \times 1000 \mu\text{m}^2$ contacted coupler region. The coupler regions have the same structure as a PCSEL element but without the PC definition process. This allows for these regions to be electrically driven from loss, through transparency, into gain in order to control the interaction of adjacent elements. The PCSEL length was chosen to minimize thermal effects between the PCSELS. This allows individual PCSEL elements to interact through the light emitted at the edges of the devices.

Figure 2 shows a plot of the LI characteristics of each of the individual PCSEL elements, demonstrating a lasing threshold of ~ 60 mA and individual powers of several mW at 300 mA. In our PCSEL design, half of the PCSEL power is lost to the substrate, and a third of vertical power is absorbed by the p-side metal contact; these issues can be improved through using substrate emission and constructively utilizing reflection from the top-contact.⁵ We observe a simultaneous increase in threshold current ($\sim 40\%$) and reduction in slope efficiency ($\sim 50\%$) for PCSEL 3 compared to PCSEL 1. This discrepancy may be due to an increase in parasitic losses (α_i or α_{\parallel}) and/or internal efficiency and is the subject of further investigation and optimization. The

observed kinks in the LI are attributed to lasing from an area smaller than the contact in these regions at small currents, which becomes more uniform as current is increased. The lasing wavelength of the three individual elements is 1067.85 ± 0.25 nm. The inset in Fig. 2 shows a plot of the measured sub threshold photonic band-structure of an individual PCSEL device, overlaid with a simulated band-structure focused around the second order Γ point using structural information from TEM shown in Fig. 1. Excellent agreement between simulation and experiment is obtained. See the Methods section.

Initially, we consider power scaling in a two element PCSEL array. Figure 3 shows two PCSEL devices, element 1 and element 2, and their connecting coupler region, coupler 1 taken into consideration. The solid lines are plots of the total power of light emitted

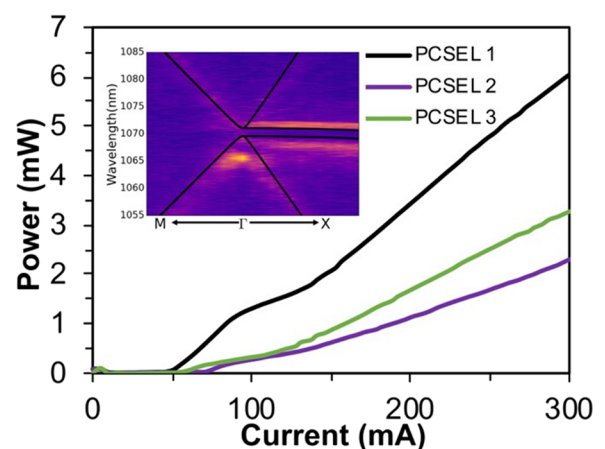


FIG. 2. LI characteristics of the individual PCSEL elements. Inset: the measured photonic bandstructure of our device in Γ -X and Γ -M directions overlaid with simulated results (black), focused around the second order Γ point.

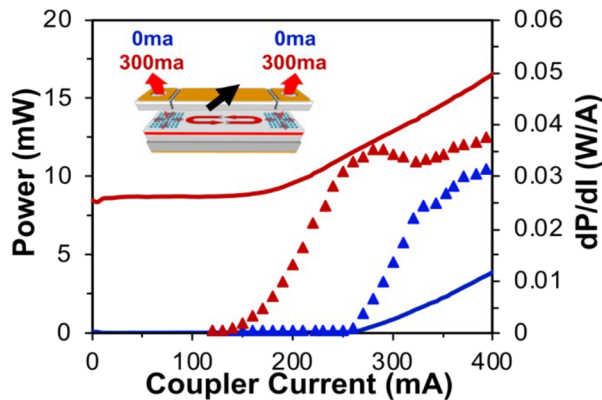


FIG. 3. Line plots show the power of light emitted from PCSEL elements 1 and 2 for varying coupler 1 current when there is no current supplied to PCSEL devices (blue) and when 300 mA is supplied to each device (red), plotted on the left axis. The scatter plot shows the differential efficiency of the system, plotted on the right axis.

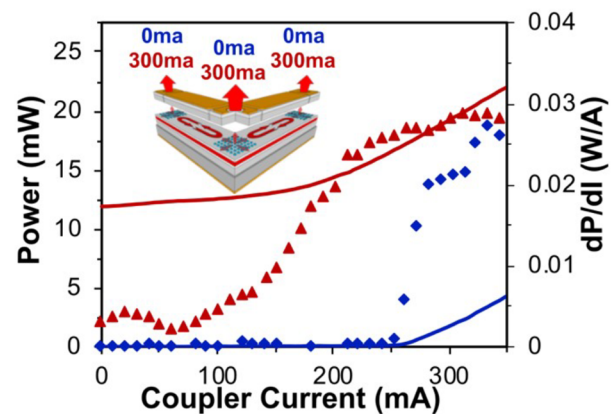


FIG. 4. Line plot shows the power of light emitted from PCSELS 1, 2, and 3 for varying coupler 1 and 2 currents when there is with no current being supplied to the PCSEL devices (blue) and when 300 mA supplied to each device (red), plotted on the left axis. The scatter plot shows the differential efficiency of the system, plotted on the right axis.

from the top surface of the PCSELS as the current to coupler 1 is varied. The symbols plot the differential efficiency of the system. It can be seen that when there is no current supplied to the PCSELS (blue), where they are acting as lossy mirrors, there is little emission from the system until the system begins to lase at ~ 250 mA with the same emission wavelength for each of the two PCSEL elements. When the PCSELS are held at 300 mA (red), the initial power is the sum of the power from each PCSEL at 300 mA (~ 250 mA above threshold). Both elements are lasing at slightly different wavelengths, separated by 0.3 nm, see S3. As the coupler current is increased, there appears to be a soft turn-on at ~ 150 mA, seen more clearly in the plot of differential efficiency. Further characterization of the device indicates a transparency current of 239 mA for the coupler, see S4. At this coupler current, the differential efficiency is 0.026 W/A, higher than that of the average of the two PCSELS (c.f. 0.020 W/A). The total power of the system at coupler transparency is 10.75 mW, an enhancement of 26% compared to the initial PCSEL power with no coupler current. The differential efficiency of the system driven in this way increases to a maximum of 0.037 W/A at 400 mA. When the coupler is above transparency, the emission from the two PCSEL elements is observed to be identical, see S3. This coincidence in wavelength is characteristic of phase-locking and coherence of PCSEL elements.^{12,13}

Figure 4 describes similar results for a system of three PCSEL elements connected as shown in the inset, with an additional PCSEL element 3 connected to PCSEL element 1 through coupler 2. The solid lines are again plots of the total power of light emitted from the surface of the three PCSEL elements, as the currents to coupler 1 and coupler 2 are concurrently varied. The symbols again plot the differential efficiency of the system. Lasing of the system with zero PCSEL current is once more observed at ~ 250 mA. When all three PCSELS are held at 300 mA (red), the initial power is the sum of the power from each of the three lasing PCSELS. As compared to the two PCSEL element system, an even softer “turn-on” is observed, with a differential efficiency of 0.026 W/A at the transparency point for the couplers (c.f. 0.019 as the average for three independent PCSEL elements and 0.020 for two coupled PCSEL elements). A maximal

differential efficiency of 0.028 W/A is observed at ~ 350 mA. The total power of the system at coupler transparency is 15.9 mW, an enhancement of 34% as compared to the three individual PCSELS alone.

The soft turn-on observed in the two and three element PCSEL arrays is attributed to the gradual increase in transparency of the coupler regions with increasing current and appears softer in the three element array due to higher power within the system. The increase in differential efficiency at transparency for the couplers is of particular interest in determining the change in α_{\parallel} . For these PCSEL elements, α_{\parallel} is calculated to be 24 cm^{-1} (see S1), and $\alpha_i = 3 \text{ cm}^{-1}$. With an internal quantum efficiency of 0.9, we obtain a value of α_{\perp} of 1.5 cm^{-1} to achieve 0.02 W/A. Utilizing the ratios of dP/dI , we can deduce a new effective α_{\parallel} for the two element array of $17.4 \pm 0.5 \text{ cm}^{-1}$ and the three element array of $16.3 \pm 0.5 \text{ cm}^{-1}$. This is in agreement with predictions that we should achieve 18 cm^{-1} and 16 cm^{-1} , respectively, see S5. These changes in α_{\parallel} correspond to an expected increase in output power that are consistent with the results of 26% for the two element array and 34% for the three element array, reported in Figs. 3 and 4, respectively. We note that scaling the array leads to effective α_{\parallel} being proportional to $1/n$ (where n is the PCSEL array order). As the coupler current is increased above transparency, not only is there a benefit due to the re-cycling of optical power lost in-plane but also amplification of this light within the coupler that provides additional power.

It has been pointed out that if power per unit area and single-mode operation can be maintained, then scaling the PCSEL area results in a proportional increase in brightness.⁵ PC design to enhance α_{\perp} along with area scaling of device size resulted in Watt-level single-mode emission,⁵ but single-mode power (and brightness) was limited by the onset of multi-modal lasing, with this being area limited. Subsequently, record single-mode powers were achieved utilizing a PC design through increased threshold gain difference between fundamental and higher order modes,⁶ allowing increased single mode area scaling. In these PC designs, as gain

difference is increased, α_{\parallel} increases, and α_{\perp} decreases. A key trade-off is therefore observed between single-mode stability and parasitic losses. By contrast, in our approach area, scaling is achieved through coherent coupling of the array, *reducing* parasitic α_{\parallel} losses.

METHODS

The MQW sample (base wafer) was grown via molecular beam epitaxy on a 3 in. (100) *n*-GaAs substrate, grown 2° off toward Γ . It consists of, from the bottom to the top, a 1400 nm *n*-Al_{0.4}Ga_{0.6}As cladding layer, 30 nm GaAs, a 3× GaAs/InGaAs quantum well active region consisting of 6.5 nm InGaAs and 31.5 nm GaAs barriers, and 160 nm of *p*-GaAs. A 2D PC slab is etched into this top GaAs layer through RIE. S2 shows a cross-sectional SEM image of a similar PCSEL device after PC definition. The wafer is then cleaned through UV ozone treatment and an HF clean before regrowth in an MOVPE reactor. The regrowth consisted of 125 nm of AlAs, alternating with 1 nm of GaAs over 9 nm of AlAs, a 1500 nm *p*-Al_{0.4}Ga_{0.6}As cladding layer, and a highly doped p++ GaAs cap layer. Following regrowth, PCSEL and coupler regions were isolated through etching of the top p++ cap layer to form isolated mesas. A 200 nm-thick SiO₂ passivation layer was then deposited across the wafer, into which separate contact windows were opened for the individual PCSELS and couplers, and *p*-type Ti/Pt/Au contacts deposited. For the PCSELS, a 60 μm-diameter circular emission aperture was defined in the top contact. A rear Ni/Au/Ge/Ni/Au *n*-type contact was then deposited to form the finished devices.

The bandstructure of our device was mapped by scanning a 200 μm multimode fiber across collimated sub-threshold emission from the surface of the PCSEL, scanning incrementally in the Γ -X and Γ -M directions to build up a bandstructure around the second order Γ point.¹⁴ Overlaid is a simulated photonic bandstructure, simulated through plane wave expansion methods.

SUPPLEMENTARY MATERIAL

The associated [supplementary material](#) details the predicted reduction in in-plane loss with array order, details of the fabrication and epitaxial processes, spectral measurements indicating coherence, method to obtain transparency current of the coupler elements, and contextualization of our results.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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