Saturday Morning, August 23, 2025

Workshop on MBE for Emerging Emitter Technologies
Room Tamaya ABC - Session WME1-SaM

Photonic-Crystal Surface-Emitting Lasers (PCSELs)
Moderator: Ricky Gibson, Air Force Research Laboratory

8:00am **WME1-SaM-1 Welcome & Opening Remarks***, **Ganesh Balakrishnan**,* University of New Mexico

8:15am **WME1-SaM-2 Passively Coupled Coherent PCSEL Arrays***, Mingsen Pan,* University of Texas at Arlington*; Chhabindra Gautam,* Semergytech, Inc.*; Thomas Rotter, Ganesh Balakrishnan,* University of New Mexico*; Shanhui Fan,* Stanford University*; **Weidong Zhou**,* University of Texas at Arlington **INVITED**

As a novel design of surface-emitting semiconductor lasers, photonic crystal surface-emitting lasers (PCSELs) feature in-plane optical feedback from photonic crystal (PC) modulation and vertical coupling with active region and emitted beams. For surface-normal emission, cavity mode in a PCSEL cavity is designed to operate at the Γ point in the momentum space. Such a cavity mode, originating from the guided resonances in PC, is coupled to radiation channels in the upward and downward directions. Thus, a surface-normal laser beam can be directed with low beam divergence which is, in theory, near the diffraction limit. One advantage of designing low divergence light source is its superior brightness in applications such as free-space optical communications and material processing [1]. The low beam divergence of a PCSEL device makes it hundreds of times brighter than the vertical cavity surface-emitting lasers (VCSELs) without collimation lens.

Monolithic PCSELs, also single PCSELs, have been demonstrated to possess high-power exceeding 50 W in continuous-wave (CW) operation and brightness of over 1 GW cm^{-2} sr^{-1} from a 3 mm diameter device aperture [2]. By designing the PC cavities, even higher output power can be achieved with larger cavity sizes. However, as the cavity size becomes larger, laser performance degrades due to the complex thermo-optical and electro-optical effects. At higher injection currents, the spatial hole burning effects create non-uniform gain distribution, thus reducing the lasing efficiency and distorting the mode profiles. High injection current induced thermal effects due to the produced high photon density at the cavity center also bring negative impacts and complexities for compensation design. On the other hand, semiconductor laser arrays are important to the applications of power scaling, which can be a promising solution to overcome the challenges in high-power PCSELs. PCSEL cavities are realized by the two-dimensional (2D) in-plane optical feedback by the PC modulation. Thus, the lateral coupling control between two PCSELs is achievable and such coupled PCSELs have been implemented by applying a waveguide connection in between for active coupling control using its optical gain/loss switching. [3]

In this paper, we investigate a compact design of coherent PCSEL arrays by placing PCSELs with suitable spacing to implement passive couplings. [4][5] The PCSEL arrays are designed on an InGaAs/GaAs multiple quantum well (MQW) platform for lasing wavelength of 1040 nm. We fabricated single PCSELs and up to 5x5 PCSEL arrays under the same processing parameters and conditions for comparison. To test the coherent operation of PCSEL arrays, we characterize the spectral linewidth properties and measure the coherency in emitted laser beam by self-interference experiments. Linewidth of 0.22 nm from a 2-by-2 PCSEL array and 0.08 nm from a single PCSEL was observed, indicating feasible coherent beam combining with narrow peak wavelength splitting from different PCSELs. The self-interference experiments test the visibility of the interference fringes, showing strong coherency of the emitted beam from the PCSEL array that is similar with a single PCSEL.

The authors acknowledge the support from JDETO and ARO.

References

[1] W. Zhou and M. Pan, "The future of photonic crystal surface-emitting lasers," *Appl. Phys. Lett.* 123, 140501, 2023.

[2] M. Yoshida, S. Katsuno, T. Inoue, J. Gelleta, K. Izumi, M. De Zoysa*, et al.*, "High-brightness scalable continuous-wave single-mode photonic-crystal laser," *Nature,* vol. 618, pp. 727-732, 2023/06/01 2023.

[3] R. J. Taylor, D. T. Childs, P. Ivanov, B. J. Stevens, N. Babazadeh, J. Sarma*, et al.*, "Coherently coupled photonic-crystal surface-emitting laser array," *IEEE J Select. Topic. Quant. Electron.* 21, pp. 493-499, 2015.

[4] C. Gautam, M. Pan, Y. Chen, T. J. Rotter, G. Balakrishnan, and W. Zhou, "Laterally coupled photonic crystal surface emitting laser arrays," *Journal of Applied Physics,* vol. 135, 2024.

[5] M. Pan, C. Gautam, Y. Chen, T. Rotter, G. Balakrishnan, and W. Zhou, "Recent Advances in Photonic Crystal Surface Emitting Lasers," *IEEE J Select. Topic. Quant. Electron.* 31, pp. 1-8, 2025.

8:45am **WME1-SaM-4 GaSb-Based Photonic Crystal Surface Emitting Diode Lasers***, **Leon Shterengas**, Gela Kipshidze,* SUNY at Stony Brook*; Aaron Stein, Dmitri Zakharov, Kim Kisslinger,* Brookhaven National Laboratory*; Gregory Belenky,* SUNY at Stony Brook **INVITED**

The development of the epitaxially regrown photonic crystal surface emitting lasers (PCSELs) based on various material systems and active region architectures is actively explored to enable device operation in wide range from visible to infrared. Our research group at Stony Brook University is involved in design and development of the GaSb-based PCSELs targeting operation at wavelength range from 2 to 4 µm. We have demonstrated air-pocket retaining epitaxial regrowth within antimonide material system and reported on diode and cascade diode PCSELs operating near 2 and 2.8 µm respectively. The first continuous wave (CW) room temperature operation of the monolithic epitaxially regrown III-V-Sb PCSELs emitting near 2 µm was reported in year 2023 and device output power was further enhanced in year 2024.The key technological capability required for development of the efficient PCSELs is a capacity to seamlessly integrate high index contrast photonic crystal layer into laser heterostructure. Approach selected by our research group for the GaSb-based monolithic PCSELs fabrication, was in many aspects like the one developed by Kyoto University group for fabrication of their record-breaking GaAs-based PCSELs. The process we adopted starts with the molecular beam epitaxial (MBE) growth of the n-cladding layer and n-side waveguide core layer, followed by the growth of the quantum well (QW) active region, which gets capped by p-side waveguide core layer. Then the incomplete laser heterostructure is removed from growth reactor, the square lattice of holes is etched in the p-side waveguide core layer, and nanopatterned incomplete laser heterostructure is reloaded back to MBE for regrowth of the p-cladding and p-contact layers. The regrowth regimes are optimized to form highly uniform array of buried voids. Increase of the PCSEL operating wavelength requites proportional increase of the period of the buried photonic crystal. However, the volume of the buried voids cannot be scaled up easily since it is affected by aspect ratio of the etched holes. Decrease of the relative size of the buried voids with respect to period of the photonic crystal (decrease of the void area fill-factor) can lead to reduction of the coupling coefficients controlling the strengths of in-plane feedback and surface emission. To obtain adequate area fill-factor of the void in the unit cell of the buried photonic crystal designed to operate at longer wavelength, several voids per unit cell can be used. The GaSb-based PCSELs based on four-voids unit cell design demonstrated the highest CW power level so far.

9:15am **WME1-SaM-6 III-V/Si Bound States in Continuum Lasers with Quantum Well (QW) and Quantum Dot (QD) Gain***, **Ashok Kodigala**,* Sandia National Laboratories **INVITED**

We demonstrate the integration of quantum well and quantum dot gain with a silicon photonic crystal (PhC) at telecommunication wavelengths near 1550nm resulting in optically pumped laser emission from symmetry-protected bound states in the continuum (BIC).

9:45am **WME1-SaM-8 Panel Discussion***,*

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