RGC Ref.: N_HKUST627_14 NSFC Ref.: 61431166003
(please insert ref. above)

The Research Grants Council of Hong Kong
NSFC/RGC Joint Research Scheme
Joint Completion Report

(Please attach a copy of the completion report submitted to the NSFC by the Mainland researcher)

Part A: The Project and Investigator(s)

1. Project Title

III-V-on-Silicon Coupled-Resonator-Optical-Waveguide Lasers for Direct-Modulated Multi-Wavelength Emission and Active Mode-Locking

2. Investigator(s) and Academic Department/Units Involved

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof. Andrew Wing On POON	Prof. Yong-Zhen HUANG
Post	Professor	Professor
Unit / Department / Institution	Department of Electronic and Computer Engineering, The Hong Kong University of Science and Technology (HKUST)	State Key Laboratory on Integrated Optoelectronics，Institute of Semiconductors, Chinese Academy of Sciences (ISCAS)
Contact Information	eeawpoon@ust.hk	yzhuang@semi.ac.cn
Co-investigator(s) *(with title and institution)*		Dr. Yue-De YANG Dr. Jin-Long XIAO State Key Laboratory on Integrated Optoelectronics，ISCAS

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	1 Jan. 2015		
Project Completion date	31 Dec. 2018		
Duration *(in month)*	48		

Deadline for Submission of Completion Report	31 Dec 2019		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. To experimentally investigate hybrid integrated InGaAsP-on-silicon coupled-resonator optical waveguide (CROW) lasers as a spectrally reconfigurable, multi-wavelength laser source, with separate direct modulations using pixelized injection patterns based on the CROW eigenstate intensity distributions

2. To experimentally investigate the CROW laser as a spatially multiplexed multi-wavelength light source, with separate direct modulations and spatially separate coupled waveguides for different coupled resonators

3. To experimentally investigate the CROW laser as a passively or actively mode-locked laser source, with the ability to generate pseudo-random pulse patterns

4. To experimentally investigate the CROW laser integrated with in-cavity silicon power monitors (by nonlinear two-photon absorption (TPA) and linear defect-state absorption) distributed along the CROW structure for feedback-controlled pixelized injection patterns

5.2 Revised Objectives

Date of approval from the RGC: ____________________

Reasons for the change: ____
____

1.
2.
3. ....

6. Research Outcome

Major findings and research outcome
(maximum 1 page; please make reference to Part C where necessary)

1. We demonstrated *multimode, continuous-wave lasing* in *heterogeneously integrated III-V-on-Si microspiral disk lasers* using spatially selective injection at room temperature. We attained a low threshold current of ~11 mA. We have published this work as part of an *invited review* article in the IEEE JSTQE2018 and also in conference proceedings (Part C).

2. Together with our NSFC project collaborators, we have *jointly demonstrated heterogeneously integrated III-V-on-Si Fabry-Perot lasers*, with increased slope efficiencies due to the enhanced mode confinement enabled by the p-electrode-covered cavity facets. We have demonstrated multimode continuous lasing and singlemode pulsed lasing with threshold currents of 45 mA and 16 mA, respectively. We have *co-authored* a Journal of Semiconductor 2018 publication (Part C).

3. We demonstrated *adhesively bonded III-V-on-silicon two-element coupled-microring lasers upon broad-beam pulsed optical pumping at room temperature*. We observed a single-mode lasing with a threshold fluence of ~0.4 mJ/cm^2. Based on this research outcome, we are currently working on molecularly bonded III-V-on-silicon multi-element coupled-microring lasers upon spatially selective pulsed optical pumping at room temperature.

4. We successfully developed a *controlled, batch process for simultaneously bonding four III-V dies to four patterned SOI dies* using both adhesive bonding and silica bonding techniques, attaining a good area retention. We *jointly* developed some of the core fabrication processes with our NSFC project collaborators, specifically the polymer adhesive bonding, based on many of their advices. The process developments underlie the Journal of Semiconductor 2018 journal publication in Outcome 2.

5. We systematically studied *all-silicon DSA microring-resonator sub-bandgap photomonitors* in the 1550nm wavelengths using various ion species for implantation. We also studied the photomonitors' responsivity under various annealing temperatures. Our experiments revealed a maximum waveguide responsivity of ~10 mA/W/mm using 7.5×10^{12} cm^{-2} of Ar ion implantation. We have published this work as part of an *invited review* article in the IEEE JSTQE2018 (Part C).

Potential for further development of the research and the proposed course of action
(maximum half a page)

There are still much room for on-going development of the research as we have alluded to above. We will continue to optimize our fabrication processes, with an immediate objective to reduce the series resistance to tens of ohms and to optimize the inter-layer coupling between the III-V gain and the silicon coupled microresonators using molecular silica bonding. We will further explore the originally proposed Objectives (1) – (4) once we have demonstrated *continuous-wave injection coupled-microresonator lasers* with single- and multi-mode lasing on an improved III-V-on-silicon photonics platform.

Leveraging the research outcomes of this project, we have successfully applied for another competitive grant (GICI-003, starting 1-1-2020) whereby we will extend on the concepts of *heterogeneous integration* and *photomonitor integration* to investigate *programmable* heterogeneously integrated III-V-on-Si microring switch arrays for next-generation high-performance computing. We have also submitted another RGC GRF (16207420) grant application in Nov. 2019 to investigate *photonics reservoir computing* using an III-V-on-silicon coupled-microring laser network.

7. The Layman's Summary

(describe <u>in layman's language</u> the nature, significance and value of the research project, in no more than 200 words)

Optical interconnects technology offers many key advantages including a high data bandwidth and potentially low-power consumption compared to the conventional electrical interconnects. Moreover, multiplexing schemes such as wavelength-division multiplexing (WDM) and spatial-division multiplexing (SDM) can further enhance the data bandwidth of optical interconnects. In this work, we laid the necessary fundamentals developing a coherent array of coupled semiconductor microlaser sources integrated on a silicon chip, with potentially tunable lasing wavelengths or multiple lasing wavelengths or a pulsed laser source output-coupled at different spatial output ports. Such on-chip laser sources, upon successful realization, can serve as a multi-functional active photonic building block in future high-data-bandwidth and low-power-consumption optical interconnects. They will enable emerging functionalities or network architectures for next-generation high-performance computing systems and big-data communications, especially for data-center interconnect applications.

Specifically, the many fabrication process know-hows developed through this work will open up many possibilities of integrating III-V semiconductor-based active photonics on silicon-based photonic devices and circuits. Our developed heterogeneous integration fabrication technology will enable us to develop technologies such as programmable III-V-on-Si photonics in the near future.

<u>Part C: Research Output</u>

8. Peer-reviewed journal publication(s) arising <u>directly</u> from this research project

(Please attach a copy of each publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)

The Latest Status of Publications	Author(s)	Title and	Submitted to	Attached	Acknowledge	Accessible

Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*	*(**bold** the authors belonging to the project teams and denote the corresponding author with an asterisk*)*	Journal/ Book *(with the volume, pages and other necessary publishing details specified)*	RGC *(indicate the year ending of the relevant progress report)*	to this report *(Yes or No)*	d the support of this Joint Research Scheme *(Yes or No)*	from the institutional repository *(Yes or No)*
2018				Z. Yao, **K. Wu**, **B. X. Tan**, J. Wang, Y. Li, Y. Zhang, **A. W. Poon***	Integrated silicon photonic microresonators: Emerging technologies, (**invited**) IEEE Journal of Selected Topics in Quantum Electronics, Vol. 24, No. 6, 5900324, Nov./Dec. 2018.	2019	Yes	Yes	Yes
2018				Y. Yang, S. Sui, M. Tang, J. Xiao, Y. Du, **A. W. Poon**, Y. Huang*	Hybrid AlGaInAs/Si Fabry–Pérot lasers with near-total mode confinements, Journal of Semiconductors 39 (8), 084001, Aug. 2018.	2019	Yes	Yes	Yes

9. Recognized international conference(s) in which paper(s) related to this research project was/were delivered *(Please attach a copy of each delivered paper. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)*

Month/Year/ Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
May/2015/San Jose, USA	Waveguide-integrated unidirectional-emission microspiral lasers for optical interconnects	CLEO- Conference on Lasers and Electro- Optics 2015	2016	Yes	Yes (acknowledged on the poster presentation)	Yes
Nov/2017/Singapore	Heterogeneously Integrated III-V-on-silicon Microspiral Disk Lasers for Optical Interconnects	PIERS- Progress In Electromagnetics Research Symposium 2017	2019	Yes	Yes	Yes
Nov/2017/Singapore	Thermal Shunts for Heterogeneously Integrated III-V-on-Silicon Microspiral Disk Lasers	PIERS- Progress In Electromagnetics Research Symposium 2017	2019	Yes	Yes	Yes
May/2018/San Jose, USA	Design Principles for Heterogeneously Integrated III-V-on-Silicon Microdisk Unidirectional Singlemode Lasers	CLEO- Conference on Lasers and Electro- Optics 2018	2019	Yes	Yes (acknowledged on the oral presentation slides)	Yes

10. Student(s) trained *(Please attach a copy of the title page of the thesis.)*

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
ZHANG Yu	PhD	1-9-2010	2-5-2016
WU Kaiyi	PhD	1-9-2015	Expected 31-8-2021
TAN Bo Xue	PhD	1-9-2016	Expected 31-8-2021
LI Jiayang	PhD	1-9-2018	Expected 31-8-2023

11. Other impact *(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, etc.)*

Best Student Paper Award 1st prize for the Optics and Photonics subcommittee at the 39th Progress in Electromagnetics Research Symposium (PIERS 2017) for the paper titled "Heterogeneously Integrated III-V-on-silicon Microspiral Disk Lasers for Optical Interconnects"

12. Statistics on Research Outputs *(Please ensure the summary statistics below are consistent with the information presented in other parts of this report.)*

	Peer-reviewed journal publications	Conference papers	Scholarly books, monographs and chapters	Patents awarded	Other research outputs (Please specify)
No. of outputs arising directly from this research project [or conference]	2	4	0	0	1 (Best Student Paper Award)