(Revised 07/09)

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# 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

Hybrid InGaAsP-silicon unidirectional-emission microcavity lasers for on-chip optical interconnects

### 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 | Associate 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) |
| Co-investigator(s) *(with title)* | | Dr. Yue-De YANG<br>Dr. Jin-Long XIAO |

### 3. Project Duration

| | Original | Revised | Date of RGC/ Institution Approval *(must be quoted)* |
|---|---|---|---|
| Project Start date | 1-1-2011 | | |
| Project Completion date | 30-12-2013 | | |
| Duration *(in month)* | 36 | | |

## Part B: The Completion Report

### 5. Project Objectives

5.1 Objectives as per original application

1. To experimentally investigate hybrid InGaAsP-silicon uni-port directional-emission microspiral resonator-based room-temperature continuous-wave electrical-injection lasers

2. To systematically investigate the microspiral lasing mechanism and output-coupling properties

5.2 Revised Objectives

Date of approval from the RGC: ____________________

Reasons for the change: ______________________________________________

__________________________________________________________________

(Revised 07/09)

## 6. Research Outcome

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

- **AlGaInAs/InP waveguide-coupled microspiral disk lasers**

We have demonstrated room-temperature cw electrically injected AlGaInAs/InP waveguide-coupled microspiral disk lasers of 30 and 40μm-radius with direct-modulation. We obtained for a 30μm-radius microspiral disk laser that was directly connected to an on-chip photodiode an estimated laser output power of at least 200 μW upon a 70mA injection. We demonstrated direct-modulation of the waveguide-coupled microspiral disk laser, with a small-signal-response 3dB bandwidth exceeding 10 GHz for a 30μm-radius microlaser. We also demonstrated, to our knowledge, the highest data transmission rate of 15 Gbit/s for direct-modulated semiconductor microresonator lasers, with a bias current of 90 mA at a stage temperature of 15 °C.

One major feature in our injection microlaser design is that we adopted ring-shaped p-contacts on top of the microspiral disk rim. This maximizes the spatial overlap between the injection current and the high-quality-factor (high-Q) optical modes of the microspiral cavity, resulting in simultaneously minimizing the lasing threshold and maximizing the modulation bandwidth. We characterized the DC and direct-modulation performances among three different ring-shaped injection designs and the conventional disk injection design. Compared to the conventional disk injection design, our outer-ring injection design for the 30μm-radius microspiral disk lasers has shown a reduced lasing threshold current from 42 to 28 mA, an improved slope-efficiency from 0.269 to 0.724 mW/A, an improved 3dB bandwidth from 8.9 to 10.7 GHz, and suggested a reduced energy consumption per bit at 10 Gbit/s from 19.1 to 8.7 pJ/bit.

We have recently published all the above major findings in a journal article in Optics Express (see Publication 1, Part C). We have also reported the preliminary results in an international conference as an oral presentation (see Conference 1, Part C).

- **AlGaInAs/InP-on-Si waveguide-coupled microspiral and circular microdisk lasers**

We have demonstrated hybrid integration of InGaAlAs and silicon using sub-hundred-nanometer BCB adhesive bonding. We have tested the bonding material quality with both InGaAlAs disk-shaped p-i-n diodes and Fabry-Perot laser structures. Our measured dark current density is below 25 μA/cm$^2$, which is comparable to that of the state-of-the-art III-V-on-Si wafer-bonded photodetectors in the literature (10 μA/cm$^2$). Our measured lasing threshold current density of the FP lasers is between 1.75 and 1.95 kA/cm$^2$, which is comparable to that of our InGaAlAs microspiral disk lasers (2 kA/cm$^2$) and also to typical values (~1.1 to 2 kA/cm$^2$) for III-V-on-silicon wafer-bonded lasers in the literature. We therefore conclude that we have attained a good wafer-bonding quality.

We have demonstrated room-temperature pulsed (10% duty-cycle at 1 MHz) electrically injected InGaAlAs-on-silicon waveguide-coupled microspiral disk lasers of 20μm radius. We measured a lasing threshold current of 33 mA and a lasing linewidth below 20 pm. We observed a 20dB side-mode suppression ratio (SMSR) at an injection current of 50 mA. We obtained a maximum fiber-coupled laser-output power of 1.8 μW at 60 mA.

We have also demonstrated room-temperature cw electrically injected InGaAlAs-on-silicon waveguide-coupled circular microdisk lasers of 25μm radius. We measured a lasing threshold current of 20 mA and a lasing linewidth below 20 pm. We observed a 20dB SMSR at an injection current of 30 mA. We obtained a maximum fiber-coupled laser-output power of 0.1 μW at 60 mA.

The performances of our current InGaAlAs-on-silicon microlasers are largely limited by the poor heat dissipation of the wafer-bonded laser gain medium. We expect this problem can be mitigated using a proper thermal shunt design, which we are currently working on.

We are currently preparing a paper submission to an international conference, and will report improved results in a journal (see Publication 2, Part C).

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

- As mentioned above, one critical further development of the research needed is to significantly improve the thermal dissipation of the wafer-bonded InGaAlAs gain medium. We propose the following course of actions including (i) designing proper thermal shunts, (ii) minimizing the serial resistance of the fabricated microlasers in order to reduce the current-induced heat, and (iii) optimizing the InGaAlAs wafer layer design and material compositions in order to obtain a high thermal conductivity.
- We will also further develop the direct-modulation capability of the hybrid InGaAlAs-silicon microspiral lasers. We will further optimize our spatially selective injection designs in order to better spatially overlap with the high-Q optical modes and to minimize the slow carrier diffusion. We will also further improve the radio-frequency (RF) impedance matching.

## 7. The Layman's Summary

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

Over the past decade, the life style of modern society has been significantly changed by the wide-spread use of computers, smart phones and the Internet, thanks to the development of information technology based on silicon micro-electronics. However, the current silicon chips are facing their limits in processing capacity due to an insufficient bandwidth and an excessive power consumption of the conventional electrical interconnection. One potential solution is to use high-bandwidth and energy-efficient integrated optical components to replace the copper wires for future on-chip interconnection.

Silicon photonics offers a promising technology platform for on-chip optical interconnects. However, silicon due to its indirect bandgap does not efficiently emit light. In order to enable on-chip laser sources, hybrid InGaAlAs-Si lasers have been demonstrated with wafer-bonding techniques and attracting significant research interests. Nonetheless, one shortcoming of the demonstrated hybrid silicon lasers using conventional optical microresonators is the bi-directional lasing emission, which is undesirable and imposes additional structures to re-route or combine the laser emissions into one laser beam. In this project, we have successfully developed hybrid InGaAlAs-Si on-chip *uni-port* directional-emission microcavity laser sources that enable direct-coupling to an integrated silicon waveguide without imposing additional structures or excess footprints.

## Part C: Research Output

### 8. Peer-reviewed journal publication(s) arising directly 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) (*bold the authors belonging to the project teams and denote the corresponding author with an asterisk**) | Title and Journal/Book (*with the volume, pages and other necessary publishing details specified*) | 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*) |
|---|---|---|---|---|---|---|---|---|
| Year of publication | Year of Acceptance (*For paper accepted but not yet published*) | Under Review | Under Preparation (*optional*) | | | | | |
| 2014 | | | | **Yue-De Yang, Yu Zhang, Yong-Zhen Huang, and Andrew W. Poon*** | "Direct-modulated waveguide-coupled microspiral disk lasers with spatially selective injection for on-chip optical interconnects," Optics Express, vol. 22, issue 1, pp. 824-838, Jan. 2014 | | Yes | Yes |
| | | | 2014 | **Yu Zhang, Yue-De Yang, Yong-Zhen Huang, and Andrew W. Poon*** | "Unidirectional emission III-V-on-silicon microspiral lasers for on-chip optical interconnects" | | No | |

### 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)*

| 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)* |
|---|---|---|---|---|---|
| June/2013/U.S. | AlGaInAs/InP waveguide-coupled unidirectional-emission microspiral lasers for on-chip optical interconnects | Conference on Lasers and Electro-Optics (CLEO) | | Yes | 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 |
|---|---|---|---|
| Yu ZHANG | PhD | 1-9-2010 | 31-8-2015 (expected) |

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

The project has attracted the sponsorship of the Hong Kong Scholars Program (2011 – 2013) for partially supporting Dr. Yue-De Yang, one of the co-investigators, as a visiting scholar to HKUST for the period of Dec. 2011 – Dec. 2013.

The project also serves as a strong basis for continuous collaboration between HKUST and ISCAS. We are currently preparing a new application to NSFC/RGC Joint Research Scheme 2014/15 based on the major findings of this project.