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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

Key Functional Photonic Elements for On-chip Mode-multiplexed Optical Interconnects

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof. TSANG Hon Ki	Prof DAI Daoxin
Post	Professor	Professor
Unit / Department / Institution	Dept. of Electronic Engineering/ The Chinese University of Hong Kong	College of Optical Science and Engineering/ Zhejiang University
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Co-investigator(s) *(with title and institution)*	Prof. SHU Chester Ching-Tat The Chinese University of Hong Kong	Prof. SHI Yaocheng Zhejiang University

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted*)
Project Start date	01/01/15	N.A.	N.A.
Project Completion date	31/12/18	N.A.	N.A.
Duration *(in month)*	48	N.A.	N.A.
Deadline for Submission of Completion Report	31/12/2019	N.A.	N.A.

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. Demonstrate on-chip mode division multiplexing (MDM) and study how to minimize mode cross talk. Evaluate experimentally how mode cross-talk, dispersion and nonlinear effects can affect capacity of MDM communications.
2. Develop novel mode add-drop multiplexers and data switching devices for MDM system.
3. Develop novel waveguide grating coupler arrays for chip-fiber input-output from MDM network on chip.
4. Fabricate and test other novel integrated functional elements required for on-chip MDM

5.2 Revised Objectives: Not Revised

6. Research Outcome

Major findings and research outcome

(maximum 1 page; please make reference to art C where necessary)

The work towards the different objectives were detailed in section 5. Here we summarize the major findings and outcomes:

(i) Mode division multiplexing is a viable method for increasing the data transport capacity for networks on chips (X. Wu, J. of Lightwave Technol., 2018; Y. Hsu, IEEE Phot Tech Lett

2018). We were able to demonstrate state of the art data transmission capacity using different modes in a photonic integrated circuit.
(ii) Switching of data from one mode to another waveguide mode is possible with the use of asymmetric directional couplers (S. Wang, Opt. Lett 2017). In the project we also demonstrated the possibility of using ten modes (Dai, Laser & Photonics Review 2018) and that bends in multimode waveguides can be possible with low intermode crosstalk (X. Wu, CLEO 2018; H.Wu Lasers & Photonics Reviews, 2019).
(iii) Mode multiplexed data in a chip can be transmitted off-chip using an array of vertical grating couplers for interface to multi-core fibers (Y. Tong, Opt Lett. 2018)
(iv) Mode divison multiplexing in multimode optical fibers can be enabled by mode selective launch from a multimode silicon waveguide and multimode grating coupler (Y.Tong, IEEE J. of Quantum Elect, 2019).

Outcomes from the project include the training of two PhD students in Hong Kong (Xinru WU, PhD 2018 and Yeyu Tong, expected PhD in 2020), and filing of a provisional US patent application for the novel multimode waveguide grating coupler. We also strengthened the collaborations between CUHK and Zhejiang University, and established collaboration with National Chiao Tung University (Taiwan) (J10, Chen et al., IEEE Access 2019).

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

The further development of mode division multiplexing for both optical networks on-chip and high capacity optical interconnects using multimode fiber may find practical applications in high performance computers and data center optical interconnects respectively.
For high performance computing, some major challenges remain. The most difficult challenge is the monolithic integration of state-of-the-art CMOS microprocessors with the optical modulators and receivers. The vastly different dimensions of state of the art fin-FETS (~7nm) and silicon optical waveguides (~500nm) may require the development of optical interconnects on a separate layer in CMOS, similar to the metal interconnect stack used in existing CMOS. Nonetheless, regardless of whether the optical interconnects are on the silicon waveguides or on a dielectric waveguide above the silicon transistor plane, the technology of mode division multiplexing have been validated by this project.

In the short term we believe that the most promising application of mode division multiplexing will be in the application of data center optical interconnects. The devices developed in this project may find applications for modulating and selectively launching high order modes in multimode fiber, and this will enable multimode fibers in data centers to surpass by manifold the capacity of the single mode fibers commonly used today.

In this project the novel multimode waveguide grating coupler developed was limited to the selective launch of only two modes per polarization in a few mode fiber. We think it will be possible with future work to increase the number of modes which can be selectively launched by using a more advanced optimized multimode waveguide grating coupler design. A new RGC GRF proposal will be submitted for the planned exploration of multimode waveguide grating couplers for multimode fibers and data center high capacity interconnects.

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)

In this project we advanced the technology of mode division multiplexing (MDM) for high capacity networks-on-chip and the technology to connect the MDM signals in silicon photonic chips with optical fibers. This technology will find near term application for high capacity optical interconnects in the next generation data centers. We demonstrated the viability of MDM for 300Gb/s per polarization per wavelength data transmission using three waveguide modes and modest bandwidth (30 GHz analog bandwidth) drive electronics. By combining wavelength division multiplexing (WDM) with MDM we demonstrated over 9.4 terabit/s data transmission capacity. We also developed novel optical interface between MDM in a silicon waveguide and optical fibers. The novel waveguide grating coupler arrays enable multicore single mode fibers to interface with on-chip MDM. We also developed a novel multimode waveguide grating coupler which could selectively launch four modes in the two polarizations of a few-modes fiber. A provisional US patent application was submitted. The multimode waveguide grating coupler has excellent potential for practical applications. It can potentially revolutionize future optical communications by enabling multimode optical fibers (conventionally regarded as slow) to use MDM in data transmission, and attain transmission capacities several times that of single mode fiber.

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.)

Sequence Number	Year of publication	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)*	Accessible from the institutional repository *(Yes or No)*
J1	2016	**Shipeng Wang**, **Hao Wu**, **H.K. Tsang, D. Dai***	"Monolithically integrated reconfigurable add-drop multiplexer for mode-division-multiplexing systems," Optics Letters 41, 5298-5301 (2016)	2016	Yes	Yes	No
J2	2017	**Xinru Wu***, C. Huang, K. Xu, **Chester Shu, Hon Ki Tsang**	"Mode-Division Multiplexing for Silicon Photonic Network-on-chip", Journal of Lightwave Technology vol. 35 pp.3223-3228	*2016* *(preprint)*	Yes	Yes	No

J3	2017	**Shipeng Wang**, Xianglian Feng, S. Gao, **Yaocheng Shi**, T. Dai, H. Yu, **H.K. Tsang**, **Daoxin Dai***	"On-chip reconfigurable optical add-drop multiplexer for hybrid wavelength/ mode-division-multiplexing systems," Opt. Lett. Vol. 42, pp. 2802-2805, 2017.	No	Yes	Yes	No
J4	2018	**Y. Hsu**, C.-Y Chuang , **Xinru Wu** , G.H. Chen, C.W. Hsu, Y.C. Chang, C.W. Chow*, J. Chen, Y.C. Lai , C.H. Yeh , **Hon Ki Tsang**	"2.6 Tbit/s On-Chip Optical Interconnect Supporting Mode-Division-Multiplexing and PAM-4 Signal," IEEE Photonics Technology Letters,30, pp. 1052-1055, 2018.	No	Yes	Yes	No
J5	2018	**X. Wu*** , C. Huang , K. Xu , W. Zhou , **C. Shu**, **H.K. Tsang**	"3 × 104 Gb/s Single-λ Interconnect of Mode-Division Multiplexed Network With a Multicore Fiber," J. of Lightwave Technology vol. 36, pp. 318-324, 2018.	No	Yes	Yes	No
J6	2018	**D. Dai***, **C.L. Li, S. Wan**g, **H. Wu**,**Y.C. Shi** Z.H. Wu, S.M.Gao T.G. Dai, H. Yu, **H.K. Tsang**	"10-Channel Mode (de)multiplexer with Dual Polarizations," Laser & Photonics Reviews vol. 12, 1700109, 2018.	No	Yes	Yes	No
J7	2019	**Yeyu Tong**, Wen Zhou, **Hon Ki Tsang***	"Efficient perfectly vertical grating coupler for multi-core fibers fabricated with 193 nm DUV lithography," Optics Letter vol. 43 pp.5309-5312 2018	No	Yes	Yes	No
J8	2019	**Hao Wu, Chenlei Li,** Lijia Song, **Hon Ki Tsang**, J.E. Bowers, **Daoxin Dai***	"Ultra-Sharp Multimode Waveguide Bends with Subwavelength Gratings, LASER & PHOTONICS REVIEWS Vol. 13 Article Number: 1800119, 2019	No	Yes	Yes	No
J9	2020	**Yeyu Tong**, Wen Zhou, **Xinru Wu, Hon Ki Tsang***	"Efficient Mode Multiplexer for Few-Mode Fibers Using Integrated Silicon-on-Insulator Waveguide Grating Coupler," IEEE Journal of Quantum Electronics, vol 56 article no 8400107 doi:10.1109/JQE.2019.2950126, 2019	No	Yes	Yes	No
J10	2019	G.H. Chen, C.W.Chow, C.H. Yeh, C.W.Peng, P.C. Guo, J.F.Tsai, M.W. Cheng, **Y. Tong**, and **H.K.Tsang**	"Mode-Division-Multiplexing (MDM) of 9.4-Tbit/s OFDM Signals on Silicon-on- Insulator (SOI) Platform" IEEE Access vol. 7, pp. 129104-129111, 2019.	No	Yes	Yes	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. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)*

Seq. Number	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)*
C1	2016/05/ San Jose, CA, USA	Mode division multiplexed 3 × 28 Gbit/s on-chip photonic interconnects	2016 Conference on Lasers and Electro-Optics (CLEO)	2016	No	Yes	No
C2	2016/07/ Niigata, Japan	Mode division multiplexing switch for on-chip optical interconnects	21st OptoElectronics and Communications Conference (OECC) & Int. Conference on Photonics in Switching (PS) 2016	2016	No	Yes	No
C3	2016/08/ Shanghai China	Integrated Hyperuniform Polarizers and Nanophotonic Mode De-multiplexers	IEEE Group Four Photonics Conference	2016	No	Yes	No
C4	2016/08/ Shanghai, China	Multiplexing and switching for mode division multiplexed optical interconnects	Progress in Electromagnetic Research Symposium (PIERS) 2016	2016	No	Yes	No
C5	2016/11/ Wuhan China	Photonic integration for Terabit scale single-wavelength on-chip Optical Interconnects	Asia Communications and Photonics Conference (ACP) 2016	2016	No	Yes	No
C6	2017/3/ Los Angeles USA	Single-lambda 312 Gb/s Discrete Multi-Tone Interconnect of Mode-Division Multiplexed Network with a Multicore Fiber	Optical Fiber Communications Conference (OFC 2017)	No	Yes	Yes	No
C7	2018/5/San Jose USA	Low Crosstalk Bent Multimode Waveguide for On-chip Mode-Division Multiplexing Interconnects	Conference on Lasers and Electro-Optics (CLEO) 2018	No	Yes	Yes	No
C8	2018/5/San Jose USA	192-Gbit/s PAM-4 Optical Interconnect using Mode-Division Multiplexing	Conference on Lasers and Electro-Optics (CLEO) 2018	No	Yes	Yes	No
C9	2019/4/ Ghent Belgium	Efficient Mode Multiplexer for Few-Mode Fibres Using Integrated Silicon-on-Insulator Grating Coupler	European Conference on Integrated Optics (ECIO), 2019.	No	Yes	Yes	No

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
Xinru WU	PhD	August 2014	September 2018
Yeyu TONG	PhD	August 2016	August 2020 (Title not yet available, but see papers J7 , C9 & J9 for topics)

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

Provisional US Patent application entitled “Multimode Waveguide Grating Coupler” was filed on 22 April 2019 (application number 62/837042)