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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

Visible-light optomechanical integrated circuits based on III-nitride semiconductors

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof. SUN Xiankai	Prof. WANG Lai
Post	Associate Professor*	Associate Professor
Unit / Department / Institution	Department of Electronic Engineering / The Chinese University of Hong Kong	Department of Electronic Engineering / Tsinghua University
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Co-investigator(s) *(with title and institution)*	Prof. TSANG Hon Ki, The Chinese University of Hong Kong	Prof. HAO Zhibiao, Tsinghua University; Prof. LUO Yi, Tsinghua University

*Promoted from Assistant Professor to Associate Professor with effect from 1 August 2020.

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	1 January 2016		
Project Completion date	31 December 2019		
Duration *(in month)*	48		
Deadline for Submission of Completion Report	31 December 2020		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. To design and fabricate integrated photonic circuits for high-efficiency fiber-to-chip coupling and low-loss on-chip routing at visible wavelengths.
2. To develop III-nitride nano-optomechanical resonators operating at visible wavelengths, and demonstrate their significantly enhanced performance compared with those fabricated in silicon.
3. To design and fabricate on-chip integrated semiconductor lasers at visible wavelengths based on III-nitrides, and further demonstrate their seamless integration with nano-optomechanical systems on the same platform.

4. To conduct both theoretical and experimental investigation on the coupling mechanisms of visible-light photons and high-frequency vibrational phonons, and further to explore new physics and applications that result from such coupling mechanisms in wide-bandgap semiconductors.

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)

The research outcome in the engineering aspect is shown as follows:

(1) Visible-light integrated photonic circuits: We designed and fabricated integrated photonic circuits for high-efficiency fiber-to-chip coupling and low-loss on-chip routing at visible wavelengths. More specifically, we have obtained fiber-to-chip grating by using on-chip grating couplers, which has a coupling efficiency of 12.7% per coupler at the center wavelength of 771.8 nm, with a 3-dB bandwidth of ~10 nm. The minimal propagation loss is 2 dB/cm measured from a straight waveguide [J1].

(2) Visible-light integrated photonic components: We also fabricated and characterized the microresonators, directional couplers, Mach–Zehnder interferometers, and mode multiplexers [J1]. In addition, we have also investigated and optimized the designs of visible-light absorbers for different applications. The optimized absorber can achieve perfect optical absorption either with an ultrabroad bandwidth covering 300–850 nm [J7, C3] or with an ultranarrow bandwidth of only 0.33 nm centered at 773 nm [J11, C8].

(3) Visible-light optomechanical resonators: We developed a gallium nitride optomechanical crystal resonator. It has a size of $3.83 \times 0.17 \times 0.13\ \mu m^3$ and a mechanical modal mass of 22.83 fg, possesses an optical mode resonating at the wavelength of 393.03 nm and the fundamental mechanical mode vibrating at 14.97 GHz. The radiation-limited optical Q factor, mechanical Q factor, and optomechanical coupling rate are 2.26×10^7, 1.30×10^4, and 1.26 MHz, respectively. Compared with silicon optomechanical crystal resonators, the fundamental mechanical modal frequency is about 3 times higher [J15, C9].

(4) Visible-light optomechanical integrated circuits with acousto-optic modulators: We also fabricated visible-light optomechanical resonators, with an optical quality factor of 4×10^4, which were acousto-optically modulated by surface acoustic modes with the modulation frequency up to 2.44 GHz [J3, C2].

(5) Etchless mechanical integrated circuits on gallium nitride: We invented a new type of mechanical waveguide structure which does not require etching of the substrate material. We also fabricated and measured mechanical (phononic) integrated circuits on gallium nitride with an etchless method, which can substantially simplify fabrication processes and enhance device yield [C1].

(6) Visible-light semiconductor lasers with optomechanics: We fabricated electrically pumped InGaN Fabry-Perot semiconductor lasers emitting at a wavelength of ~428 nm on an optomechanical integration compatible platform. We investigated cavity optomechanics in a semiconductor laser, where the inverted carriers interact collectively with the photons and phonons via the carrier relaxation oscillation and optical gain effects [J10].

The research outcome in the science aspect is shown as follows:

(7) Topological physics in nanomechanical array: We fabricated two-dimensional arrays of nanomechanical nitride membranes on a chip and used optomechanical coupling to map the intensity of the elastic waves in the arrays. We experimentally discovered a series of new topological phenomena, such as dual-band integrated valley Hall nanomechanical topological insulators [J4], adiabatic transition between distinct topological edge states [J5], backscattering-immune chiral edge states [J6].

(8) Optomechanical control and manipulation of phonons in nanomechanical array: We exploited particle-nonconserving optomechanical interactions to engineer not only the band structure but also the dissipation of acoustic waves. We found a topologically protected edge state for phonons that can be parametrically amplified, which can be exploited for topologically protected acoustic wave amplification [J8, C5].

(9) Parity-time-symmetric optomechanical array: We theoretically investigated optical control of parity-time-symmetric mechanical array with gain/loss provided by the cavity optomechanical effect. We found the property of unidirectional reflection in these systems, which may pave the way for the study of topological acoustics and phononic signal processing [J12, C6].

(10) Parity-time-symmetric lasers for optomechanics: We theoretically studied a new type of semiconductor lasers where both the real and imaginary parts of the refractive index are modulated along the radial direction [J14]. We analyzed their modal properties, finding that they can achieve high modal discrimination [J13, C7] and obtain giantly enhanced sensitivity in rotation sensing, which can be used for optomechanical sensors [J9, C4].

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

In this project, we have developed optomechanical integrated circuits and devices operating in the visible wavelength range. Further development of the research can include sensing applications:

(1) Optomechanical sensing: the sensing mechanism is based on a direct relation between the shift of the mechanical resonant frequency and the variation of a mechanical quantity, such as mass, displacement, or acceleration. An on-chip implementation of optomechanical sensing will lead to enhanced sensitivity.

(2) Microfluidic biosensing: operation in the visible wavelength enables simultaneous photonic and mechanical detection in water, because the electromagnetic absorption by water is minimum at the wavelength of ~460 nm, which is 4 orders of magnitude lower than that at the wavelength of 1550 nm. This ultralow optical absorption enables high-quality-factor photonic cavities for microfluidic biosensing.

In addition to the above sensing applications, further development of the research can also include photonic crystals, nonlinear photonics, and quantum photonics. For example, the advantages of a wideband transparency window and $\chi^{(2)}$ nonlinearity of gallium nitride enable a photonic integrated circuit with functions of optical frequency synthesis through the sum- or difference-frequency generation. Operated reversely, such a photonic circuit can be used to generate entangled photon pairs or single photons on a chip by spontaneous parametric down-conversion, which is particularly useful for quantum information processing.

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)

Mechanics studies the behavior of structures when subjected to forces or displacements. With the development of nanotechnologies, people have gained the capabilities to create and control mechanical structures at the nanoscale for precision measurements of force, mass, and displacement. Combining the advantages of nanophotonics and nanoelectromechanics, optomechanical integrated circuits were developed to integrate photonic components and nanomechanical resonators on a single chip for strong optomechanical and electromechanical coupling. However, the operational light was usually in the infrared band (wavelength ~1550 nm), which limits device miniaturization and application in areas like optical imaging, biosensing, and quantum information processing.

In this project, we broke the above limitations by developing optomechanical integrated circuits and devices operating at visible wavelengths (400–780 nm). More specifically, we have experimentally realized visible-light optomechanical integrated circuits and devices on a chip, with low-loss interfaces to optical fibers. Such visible-light optomechanical integrated circuits are compatible with both passive and active integrated photonics in the visible wavelength range, including the demonstrated integrated photonic components, optomechanical resonators, and semiconductor lasers. These visible-light optomechanical integrated circuits and devices feature miniaturized device sizes and enhanced functionalities for various on-chip applications such as communication, sensing, and signal processing.

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)*	Accessible from the institutional repository *(Yes or No)*
Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*						
		Y		Yue Yu, Zejie Yu, **Lai Wang**, and **Xiankai Sun***	"Ultralow-loss etchless lithium niobate integrated photonics at near-visible wavelengths"		No	Yes	No
		Y		Yang Liu, **Lai Wang***, Yuantao Zhang*, Xin Dong, **Xiankai Sun**, **Zhibiao Hao**, **Yi Luo**, Changzheng Sun, Yanjun Han, Bing Xiong, Jian Wang, and Hongtao Li	"Demonstration of n-Ga_2O_3/p-GaN diode by wet-etching lift-off and transfer-print technique"		No	Yes	No
		Y		Yue Yu, **Lai Wang**, and **Xiankai Sun***	"Demonstration of on-chip gigahertz acousto-optic modulation at near-visible wavelengths"		No	Yes	No

	2020			Jingwen Ma, Xiang Xi, and **Xiankai Sun***	(J4) "Experimental demonstration of dual-band nanoelectromechanical valley-Hall topological metamaterials," Advanced Materials		No	Yes	No
		Y		Jingwen Ma, Xiang Xi, Yuan Li, and **Xiankai Sun***	"Nanomechanical topological insulators with an auxiliary orbital degree of freedom"		No	Yes	No
	2020			Xiang Xi, Jingwen Ma, Shuai Wan, Chun-Hua Dong, and **Xiankai Sun***	(J6) "Observation of chiral edge states in gapped nanomechanical graphene," Science Advances		No	Yes	No
2020				Yue Yu, Zejie Yu, and **Xiankai Sun***	(J7) "Nonmetallic broadband visible-light absorbers with polarization and incident angle insensitivity," IEEE Photonics Journal 12 (6): 2200807, Dec. 2020		Yes	Yes	Yes
2020				Jingwen Ma, Ziyao Feng, Yuan Li, and **Xiankai Sun***	(J8) "Optically controlled topologically protected acoustic wave amplification," [invited] IEEE Journal of Selected Topics in Quantum Electronics 26 (5): 7600410, Sep./Oct. 2020		Yes	Yes	Yes
2020				Ziyao Feng and **Xiankai Sun***	(J9) "Giant enhancement of rotation sensing with PT-symmetric circular Bragg lasers," Physical Review Applied 13 (5): 054078, May 2020		Yes	Yes	Yes
2019				Xiang Xi, Jingwen Ma, and **Xiankai Sun***	(J10) "Carrier-mediated cavity optomechanics in a semiconductor laser," Physical Review A 99 (5): 053837, May 2019		Yes	Yes	Yes

2018				Aosong Feng, Zejie Yu, and **Xiankai Sun***	(J11) "Ultranarrow-band metagrating absorbers for sensing and modulation," Optics Express 26 (22): 28197-28205, Oct. 2018		Yes	Yes	Yes
2018				Ziyao Feng, Jingwen Ma, and **Xiankai Sun***	(J12) "Parity-time-symmetric mechanical systems by the cavity optomechanical effect," Optics Letters 43 (17): 4088-4091, Sep. 2018		Yes	Yes	Yes
2018				Ziyao Feng, Jingwen Ma, Zejie Yu, and **Xiankai Sun***	(J13) "Circular Bragg lasers with radial PT symmetry: design and analysis with a coupled-mode approach," Photonics Research 6 (5): A38-A42, May 2018		Yes	Yes	Yes
2016				Jiahua Gu, Xiang Xi, Jingwen Ma, Zejie Yu, and **Xiankai Sun***	(J14) "Parity-time-symmetric circular Bragg lasers: a proposal and analysis," Scientific Reports 6: 37688, Nov. 2016	2017-12-31	Yes	Yes	Yes
2016				Wen Zhou, Zejie Yu, Jingwen Ma, Bingqing Zhu, **Hon Ki Tsang**, and **Xiankai Sun***	(J15) "Ultraviolet optomechanical crystal cavities with ultrasmall modal mass and high optomechanical coupling rate," Scientific Reports 6: 37134, Nov. 2016	2017-12-31	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 2021, San Jose, CA, USA	Ziyao Feng, Yang Liu, **Lai Wang**, and **Xiankai Sun***, "Phononic integrated circuitry with an etchless fabrication process" (submitted)	CLEO 2021		No	Yes	No
May 2021, San Jose, CA, USA	Yue Yu, **Lai Wang**, and **Xiankai Sun***, "Demonstration of on-chip gigahertz acousto-optic modulation at near-visible wavelengths" (submitted)	CLEO 2021		No	Yes	No
May 2021, San Jose, CA, USA	Yue Yu, Zejie Yu, and **Xiankai Sun***, "Nonmetallic broadband visible-light absorbers with polarization and incident angle insensitivity" (submitted)	CLEO 2021		No	Yes	No
Mar. 2021, San Francisco, CA, USA	(C4) Ziyao Feng and **Xiankai Sun***, "Rotation sensing with PT-symmetric circular Bragg lasers" [invited] (accepted)	SPIE Photonics West 2021		Yes	Yes	No
May 2020, San Jose, CA, USA	(C5) Jingwen Ma, Ziyao Feng, Yuan Li, and **Xiankai Sun***, "Topologically protected acoustic wave amplification in an optomechanical array"	CLEO 2020		Yes	Yes	No
Sep. 2019, Washington, DC, USA	(C6) Ziyao Feng, Jingwen Ma, and **Xiankai Sun***, "Parity-time-symmetric mechanical array with the cavity optomechanical effect"	Frontiers in Optics 2019		Yes	Yes	No
Sep. 2019, Washington, DC, USA	(C7) Ziyao Feng, Jingwen Ma, Zejie Yu, and **Xiankai Sun***, "Parity-time-symmetric circular Bragg lasers: enhanced modal discrimination between azimuthal modes"	Frontiers in Optics 2019		Yes	Yes	No

May 2019, San Jose, CA, USA	(C8) Aosong Feng, Zejie Yu, and **Xiankai Sun***, "Ultranarrow-band metagrating absorbers for sensing and modulation"	CLEO 2019		Yes	Yes	No
Jan. 2018, San Francisco, CA, USA	(C9) Zejie Yu, Wen Zhou, **Hon Ki Tsang**, and **Xiankai Sun***, "Recent progress in nano-optomechanical devices at microwave frequencies" [invited]	SPIE Photonics West 2018	2017-12-31	Yes	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 Zejie	Ph.D.	1 August 2015	31 July 2019
XI Xiang*	Ph.D.	1 August 2015	31 July 2021
MA Jingwen*	Ph.D.	1 August 2016	31 July 2021
YU Yue*	Ph.D.	1 August 2017	31 July 2021
FENG Ziyao*	Ph.D.	1 August 2017	31 July 2021

*These students have been trained under this project. They published journal and/or conference papers for this project. However, they have not submitted the Ph.D. thesis yet. As a result, the title page of the thesis is not available by the time when this completion report is submitted.

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

1. In this project, we collaborated with Prof. Chun-Hua Dong's group at University of Science and Technology of China, Hefei, Anhui, China. The collaborated paper is [J6] in Sec. 8.
2. In addition to those list in Sec. 9, we also presented an invited conference talk with no conference paper/abstract:
   Xiankai Sun*, "Photonics Meets Mechanics in the Nanoworld," Asia Communications and Photonics Conference Workshop 9: On-chip Light-matter Interaction: Physics and Devices, Wuhan, China, Nov. 2016

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]	15 (including submitted and accepted)	9 (including submitted and accepted)	0	0	1 invited conference talk