| RGC Ref.: N HKU712/16<br>NSFC Ref. : 61631166003 |
|---|
| *(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

Ultrafast spectro-temporal measurement based on photonic integration
基於光子集成的超快時域光譜測量的研究

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

| | Hong Kong Team | Mainland Team |
|---|---|---|
| Name of Principal Investigator *(with title)* | Prof. Kenneth Kin-Yip Wong | Prof. Xinliang Zhang |
| Post | Head of Department of Electrical and Electronic Engineering | Dean of School of Optical and Electronic Information |
| Unit / Department / Institution | Department of Electrical and Electronic Engineering, The University of Hong Kong (HKU) | Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology (HUST) |
| Contact Information | kywong@eee.hku.hk | xlzhang@mail.hust.edu.cn |
| Co-investigator(s) *(with title and institution)* | Prof. Xiaoming Wei | Prof. Chi Zhang |

### 3. Project Duration

| | Original | Revised | Date of RGC/ Institution Approval *( must be quoted)* |
|---|---|---|---|
| Project Start date | 1/1/2017 | | |
| Project Completion date | 31/12/2020 | | |
| Duration *(in month)* | 48 months | | |
| Deadline for Submission of Completion Report | 31/12/2021 | | |

## Part B: The Completion Report

## 5. Project Objectives

### 5.1 Objectives as per original application

*1.* To optimize nonlinear four-wave mixing waveguide. It is specifically about establishing the simulation model to design the nonlinear waveguide with larger nonlinear coefficient and smaller dispersion, to eventually realize the large conversion bandwidth.

*2.* To fabricate some essential components and construct the PASTA system. The nonlinear waveguide will be fabricated and some other essential passive components will be replaced based on the photonic integration technology, e.g. coupler, filter, isolator, and the inter-chip coupling technique. Consequently, the PASTA system will be constructed at the end of this stage.

*3.* To explore the ultrafast time-stretch microscopy based on PASTA. The PASTA system will be applied in the ultrafast time-stretch microscopy and it will be replaced by incoherent sources. The enlarged observation bandwidth of the PASTA system will also help to achieve larger imaging field-of-view.

*4.* To explore the real-time full-field information characterization of short pulses leveraging the PASTA system. The PASTA system will not only enlarge the dispersion-induced diversity, but also help to improve the converging speed and accuracy.

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. The nonlinear waveguide's model was established to study the influence of the nonlinear effect on the system. Besides, a silicon-based nonlinear waveguide with flat dispersion was optimized to achieve a large spectral observation bandwidth (21nm) and a high spectral resolution (1.3pm). This work is referred to *IEEE Photonics Journal, 11(5), 7102710 (2019)*.
2. The system parameters, including observation bandwidth, resolution, precision, and dynamic range were improved. According to the perfect theoretical, the bandwidth could be extended to 70 nm by utilizing non-degenerate FWM, third-order dispersion compensation scheme, time-division multiplexing technology, and phase modulator. This work is referred to *Applied Physics Letters, 114(2), 021105(2019)* and *Optics express, 27(21), 30441-30448(2019).* Besides, the measure precision was improved to 0.04 pm with phase-locked loop and temperature feedback control, which was referred to *IEEE Photonics Technology Letters, 29(22), 1971-1974(2017)*.
3. The system observation record length was extended by a panoramic-reconstruction temporal imaging. This enhancement could achieve scalable temporal record length while maintaining the sub-picosecond temporal resolution, thus overcoming the limitation of time-bandwidth product in conventional temporal imaging systems. This work is referred to *Nature communications, 8(1), 1-10(2017)*.
4. A real-time spectro-temporal analyzer has been constructed for complex spectral dynamics measurement. In contrast to the conventional PASTA system that is mainly suitable for continuous wave or quasi-CW spectral components, this system accommodated spectral component with diverse time scale, i.e. from femtosecond pulses to CW components, which significantly broaden the application area of PASTA technique. This work is referred to *Optics Express, 25(23), 29098-29120(2017)*.

5. Four-wave mixing Bragg-scattering was adopted to construct a more compact PASTA system. With this method, the second FWM stage was removed, thus the spectral detection bandwidth was improved to 30 nm and the detection sensitivity has also been enhanced by 10 dB. This work is referred to Optics Letters, 43 (8), 1922–1925(2018).
6. The improved ultrafast temporal spectral analysis system was applied to the ultrafast time-stretch microscopy. The high-speed observation of onion epidermal cells, fisheyes, and other biological samples were observed. The experiment proved that the imaging effect was improved compared with the traditional methods. This work is referred to *Optics Letters, 44(11), 2919-2922(2019)*.
7. We worked with professor Xinliang Zhang and professor Chi Zhang in a variety of ways including international conferences, the exchanges of visits, students send. Moreover, we had attended many international optical conference forums and had presentations about ultrafast spectroscopy and applications. All those activities are helpful to the further research of PASTA.

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

1. The system performance can be further improved with nonlinear enhanced waveguide and integrated large dispersion device. Fiber is not an ideal dispersion media for PASTA due to the instability of long-distance transmission and higher-order dispersion. With those integrated devices, the system performance can be improved, and a chip-based PASTA can be designed, thus this technique can provide widespread applications requiring real-time spectral analysis.
2. The framerate can be further improved to GHz with micro-cavity comb. The system framerate is determined by the repetition rate of the pump source. The current system framerate is less than 100MHz, limited by the fiber-based mode-locked laser. With micro-cavity comb, the system framerate can be improved to GHz, which is a potential tool for ultrafast spectral analysis.
3. The system can be more flexible by designing nonlinear waveguide in the other wavelength region. By virtue of the advanced technology in optical communication band, the current system can work well in C band. But the spectral observation of the other optical bands is also required in many imaging systems, including stimulated Raman scattering microscopy and fluorescence microscopy. With nonlinear waveguides in the appropriate band, the application of PASTA can be extended, and the imaging systems can be further developed.

## 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)*

This research aims to construct a spectro-temporal analyzer which is one million times faster than existing spectroscopy. Such analyzer could be leveraged in medical diagnosis, atmospheric monitoring, vivo imaging and other industrial applications. To make it more applicable to more scenarios, a non-linear waveguide model was established and compact the whole system. Besides, the performance of the analyzer was enhanced in terms of its observation bandwidth, spectral resolution, precision, dynamic range, record length, and compactness.

## 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*) | | | | | | |
| 2017 | | | | Bowen Li, Shu-Wei Huang*, Yongnan Li, Chee Wei Wong*, **Kenneth K.Y. Wong*** | Panoramic-reconstruction temporal imaging for seamless measurements of slowly-evolved femtosecond pulse dynamics, Nature Communications 8, 61 | 2018 | No | Yes | Yes |
| 2017 | | | | **Xiaoming Wei,** Bowen Li, Ying Yu, **Chi Zhang,** Kevin K. Tsia, **Kenneth K.Y. Wong*** | Unveiling multi-scale laser dynamics through time-stretch and time-lens spectroscopies, Optics Express 25 (23), 29098-29120 | 2018 | No | Yes | Yes |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2018 | | | | Bowen Li, Yuan Wei, Jiqiang Kang, **Chi Zhang, Kenneth K. Y. Wong*** | Parametric spectrotemporal analyzer based on four-wave mixing Bragg scattering, Optics Letters 43 (8), 1922-1925 | 2018 | No | Yes | Yes |
| 2019 | | | | Yuan Wei, Bowen Li, Pingping Feng, Jiqiang Kang, **Kenneth K. Y. Wong*** | Broadband dynamic spectrum characterization based on gating-assisted electro-optic time lens, Applied Physics Letters 114 (2), 021105 | 2018 | No | Yes | Yes |
| 2019 | | | | Haidong Zhou, Ningning Yang, Guoqing Liu, Liao Chen, Yi Wang, **Chi Zhang***, **Kenneth K. Y. Wong**, Xinliang Zhang | Large-temporal-numerical-aperture parametric spectro-temporal analyzer based on silicon waveguide, IEEE Photonics Journal, 11(5), 1-10. | 2018 | No | Yes | Yes |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2019 | | | | Ningning Yang, Liao Chen, Lun Li, Yaoshuai Li, **Chi Zhang***, Yi Wang, **Kenneth K. Y. Wong**, Xinliang Zhang | Time-division-multiplexed observation bandwidth for ultrafast parametric spectro-temporal analyzer. Optics Express, 27(21), 30441-30448. | | Yes | Yes | Yes |
| 2019 | | | | Pingping Feng, Jiqiang Kang, Sisi Tan, Yuxuan Ren, Chi Zhang, **Kenneth K. Y. Wong*** | Dual-comb spectrally encoded confocal microscopy by electro-optic modulators. Optics Letters, 44(11), 2919-2922 | | Yes | Yes | Yes |
| 2019 | | | | Bowen Li, Jiqiang Kang, Sheng Wang, Ying Yu, Pingping Feng, **Kenneth K. Y. Wong*** | Unveiling femtosecond rogue-wave structures in noise-like pulses by a stable and synchronized time magnifier. Optics Letters, 44(17), 4351-4354 | | Yes | Yes | Yes |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2019 | | | | Ying Yu, Cihang Kong, Bowen Li, Jiqiang Kang, Yuxuan Ren, Zhichao Luo, **Kenneth K. Y. Wong*** | Behavioral similarity of dissipative solitons in an ultrafast fiber laser. Optics Letters, 44(19), 4813-4816 | | Yes | Yes | Yes |
| 2019 | | | | Can Li, et al., and **Kenneth K. Y. Wong*** | High Energy Noise-Like Pulse Generation from a Mode-Locked Thulium-Doped Fiber Laser at 1.7 μm Photonics Journal, 11(6). | | Yes | Yes | Yes |
| 2020 | | | | Can Li, et al., and **Kenneth K. Y. Wong*** | High-energy all-fiber gain-switched thulium-doped fiber laser for volumetric photoacoustic imaging of lipids Photonic Research, Vol. 8, No. 2, 160-164, | | Yes | Yes | Yes |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2020 | | | | Ryan K. Y. Chan, Hongsen He, Yuxuan Ren, Cora S. W. Lai, Edmund Y. Lam, **Kenneth K. Y. Wong*** | Axially resolved volumetric two-photon microscopy with an extended field of view using depth localization under mirrored Airy beams. Optics Express. 28(26), 39563-39573. | | Yes | Yes | Yes |
| 2020 | | | | Hongsen He, et al., and **Kenneth K. Y. Wong*** | Resolution enhancement in an extended depth of field for volumetric two-photon microscopy. Optics Letters, 45(11), 3054-3057 | | Yes | Yes | Yes |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2020 | | | | Cihang Kong, et al., and **Kenneth K. Y. Wong*** | High-contrast, fast chemical imaging by coherent Raman scattering using a self-synchronized two-colour fibre laser. Light: Science & Applications, 9(1), 1-12 | | Yes | Yes | Yes |
| 2020 | | | | Jiawei Shi, et al., and **Kenneth K. Y. Wong*** | Grüneisen-relaxation photoacoustic microscopy at 1.7 µm and its application in lipid imaging. Optics Letters, 45(12), 3268-3271 | | Yes | Yes | Yes |
| 2020 | | | | Yi Zhou, Yuxuan Ren, Jiawei Shi, Huade Mao, **Kenneth K. Y. Wong*** | Buildup and dissociation dynamics of dissipative optical soliton molecules. Optica, 7(8), 965-972 | | Yes | Yes | Yes |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2020 | | | | Yi Zhou, Yuxuan Ren, Jiawei Shi, **Kenneth K. Y. Wong*** | Breathing dissipative soliton explosions in a bidirectional ultrafast fiber laser. Photonics Research, 8(10), 1566-1572 | | Yes | Yes | Yes |
| 2021 | | | | Mingsheng Li et al., and **Kenneth K. Y. Wong*** | Near-infrared double-illumination optical-resolution photoacoustic microscopy. Journal of Bio photonics, 14(3), e202000392 | | Yes | Yes | Yes |
| 2021 | | | | Huade Mao et al., and **Kenneth K. Y. Wong*** | Broadband meta-converters for multiple Laguerre-Gaussian modes. Photonics Research, 9(9), 1689-1698_ | | Yes | Yes | Yes |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2021 | | | | Sheng Wang, Xin Dong, Bowen Li, **Kenneth K. Y. Wong*** | Polarization-independent parametric time magnifier based on four-wave mixing. Optics Letters, 46(22), 5627-5630 | | 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)* |
|---|---|---|---|---|---|---|
| July/2017/Singapore | Observation of dissipative Kerr soliton evolution with panoramic-reconstruction temporal imaging (PARTI) | Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR) | 2018 | No | Yes | No |
| May/2018/San Jose | Ultrafast spectro-temporal analyzer for the multi-scale laser dynamics studies | Conference on Lasers and Electro-Optics (CLEO) | 2018 | No | Yes | Yes |
| July/2018/Zurich | Ultrafast spectral analysis based on swept-pump four-wave mixing Bragg scattering | Signal Processing in Photonic Communications, Advanced Photonics Congress (APC) | 2018 | No | Yes | Yes |

| | | | | | | |
|---|---|---|---|---|---|---|
| July/2018/Hong Kong | Real-time spectral analysis based on time-lens enhanced dispersive Fourier transform | Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR) | 2018 | No | Yes | Yes |
| July/2018/Hong Kong | Ultrafast optical tomography using Raman-assisted temporal magnification | Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR 2018) | | Yes | Yes | Yes |
| July/2018/Hong Kong | Stable and Synchronized Time-lens Source for Real-Time Characterization of Noise-Like Pulses | Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR 2018) | | Yes | Yes | Yes |
| Sep/2018/Washington | 1.7-µm gain-switched thulium-doped fiber laser with electrically tuning and its application to spectroscopic photoacoustic imaging | Frontiers in Optics / Laser Science (FiOLS 2018) | | Yes | Yes | Yes |
| May/2019/San Jose | 1.7-µm high-power laser generation from a thulium-assisted optical parametric oscillator (TAOPO) for bond-selective photoacoustic microscopy | Conference on Lasers and Electro-Optics (CLEO 2019) | | Yes | Yes | Yes |
| May/2019/San Jose | Resolving the temporal structure of noise-like pulse using a synchronized time magnifier | Conference on Lasers and Electro-Optics (CLEO 2019) | | Yes | Yes | Yes |
| July/2019/Hawaii | Temporal structured illumination time-stretch microscopy | Nonlinear Optics 2019 | | Yes | Yes | Yes |

| | | | | | | |
|---|---|---|---|---|---|---|
| April/2020/ Fort Lauderdale | Contrast-enhanced nonlinear photoacoustic microscopy at 1.7 μm enabled by a high-power gain-switched laser | Biophotonics Congress: Biomedical Optics 2020 | | Yes | Yes | Yes |
| May/2020/San Jose | Two-photon microscopy using hollow Gaussian beam | Conference on Lasers and Electro-Optics (CLEO 2020) | | Yes | Yes | Yes |
| May/2020/San Jose | 3D reconstruction for volumetric two-photon microscopy using dual Airy beam | Conference on Lasers and Electro-Optics (CLEO 2020) | | Yes | Yes | Yes |
| August/2020 /Sydney | Back-action of dielectric microparticles mediated by photonic nanojet | Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR 2020) | | Yes | Yes | Yes |
| August/2020 /Sydney | Volumetric two-photon microscopy with expanded field of view using dual Airy beam | Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR 2020) | | Yes | Yes | Yes |
| Sep/2020/Washington | Hysteresis in backaction force mediated by photonic nanojet | Frontiers in Optics / Laser Science (FiOLS 2020) | | Yes | Yes | Yes |
| Sep/2020/Washington | Scattering resilient single pixel imaging with a gain-switched thulium-doped fiber laser | Frontiers in Optics / Laser Science (FiOLS 2020) | | Yes | Yes | Yes |
| May/2021/San Jose | Spatially-chirped modulation microscopy at 2 μm | Conference on Lasers and Electro-Optics (CLEO 2021) | | Yes | Yes | Yes |
| May/2021/San Jose | Phase sensitive two-photon microscopy | Conference on Lasers and Electro-Optics (CLEO 2021) | | Yes | Yes | Yes |

| | | | | | | |
|---|---|---|---|---|---|---|
| May/2021/San Jose | Spectrally encoded quantitative phase imaging microscopy using 2-µm fiber laser | Conference on Lasers and Electro-Optics (CLEO 2021) | | Yes | Yes | Yes |
| July/2021/Hong Kong | Non-interferometric quantitative phase imaging at 1 µm wavelength regime | Optoelectronics and Communications Conference (OECC 2021) | | 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 |
|---|---|---|---|
| Bowen LI | PhD | September 1, 2013 | August 31, 2017 |
| Sisi TAN | PhD | September 1, 2014 | August 31, 2018 |
| Yuan WEI | MPhil | September 1, 2016 | August 31, 2018 |
| Ying YU | PhD | September 1, 2015 | August 31, 2019 |
| Cihong KONG | PhD | September 1, 2015 | August 31, 2019 |
| Pingping FENG | PhD | September 1, 2016 | August 31, 2020 |

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

NA

## 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] | 20 | 21 | 0 | 0 | 0 |