CRF 8G (Revised Sep 15)

RGC Reference HKUST2/CRF/11G
please insert ref. above

The Research Grants Council of Hong Kong
Collaborative Research Fund Group Research Projects
Completion Report

(*for completed projects only*)

Part A: The Project and Investigator(s)

1. Project Title

Controlling scattering and absorption cross sections using simple artificial structures

2. Investigator(s) and Academic Department/Units Involved *(please highlight approved changes in the composition of the project team and quote the date when RGC granted approval of such changes)*

Research Team	Name/Post	Unit/Department/Institution	Average number of hours per week spent on this project in the current reporting period
Project Coordinator	Prof. Chan Che-ting / Chair Professor	Physics Department / HKUST	10
Co-Principal investigator(s)	Prof. Chan Ho-bun / Associate Professor	Physics Department / HKUST	6
	Prof. Cheah Kok-wai / Chair Professor	Physics Department / HKBU	2
	Prof. Ng Tsz Fai / Assistant Professor	Physics Department / HKBU	5
	Prof. Pun Yue-bun / Chair Professor	Electronic Engineering Department / CityU	4
	Prof. Sheng Ping / Dr William M W Mong Chair Professor of Nanoscience	Physics Department / HKUST	5
	Prof. Tam Hoi Lam / Research Assistant Professor	Physics Department / HKBU	5
	Prof. Tam Wing-yim Professor	Physics Department / HKUST	10
	Prof. Wen Wei-jia / Professor	Physics Department / HKUST	2
	Prof. Wong Kam-sing / Professor	Physics Department / HKUST	5

	Prof. Yang Zhiyu / Professor	Physics Department / HKUST	4
Collaborators/ Others	Prof. Li Tsan-hang / Senior Lecturer	School of Physics and Astronomy / University of Birmingham*	

* RGC approved the request to change Prof. Jensen Li from Co-Investigator to an External Collaborator in April, 2013 [see Appendix I - RGC letter]

3. Project Duration

	Original	Revised	Date of RGC Approval *(must be quoted*)
Project Start Date	February 1, 2012		
Project Completion Date	January 31, 2015		
Duration (*in month*)	36 months		
Deadline for Submission of Completion Report	January 31, 2016		

Part B: The Final Report

5. Project Objectives

5.1 Objectives as per original application

1. Design artificial structures based on simple structures and materials that can modify significantly the scattering and absorption cross section of other objects. The artificial structure can either be a coating or a self-supporting structure. We will consider both electromagnetic waves and acoustic waves.
2. Develop theoretical, numerical and fabrication techniques that facilitate the realization of these structures.
3. Experimentally fabricate and characterize these structures.
4. Realize new, interesting and unusual effects using such structures.

5.2 Revised objectives

Date of approval from the RGC: _____

Reasons for the change: _____
_____

1.
2.
3. ....
N/A

6. Research Outcome

6.1 Major findings and research outcome

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

The collaboration of theorists and experimentalists results in new structures with new wave manipulations capability for acoustic and EM waves. A wide frequency range is covered: from a few hundred Hz in acoustic waves, to much higher frequencies in a broad spectrum of EM waves (GHz, THz, IR and optical frequencies). Some of our results are published in high impact journals and also resulted in patents and technology transfer. In the following, we highlight some noteworthy outputs:

New structures: The theory and experimental collaboration led to the discovery of two mechanisms for designing new artificial structures that can strongly increase the absorption cross-section for low frequency sound [Nat. Mater. 13, 873(2014), Nat. Commun. 3, 756 (2012)]. Aside from their academic value, our works in this regard have initiated some applications in the use of acoustic metamaterials towards low frequency noise mitigation. In particular, a company has been incorporated by one of our former PhD students, Acoustic Metamaterials Ltd., to fabricate sound absorbing panels. The company has been admitted into the Hong Kong Science Park. We also introduced a new scheme called "space-coiling" which can be used to generate metamaterials with extreme effective parameters. Combined with resonances, the space-coiling structures can generate refractive indices from large positive to zero to negative values. The idea is published as a theoretical proposal [Phys. Rev. Lett. 108, 114301, 2012] and subsequently as an experimental realization [Sci. Rep. 3, 1614 (2013)]. We have developed a new route in constructing metasurfaces using "geometric-phase elements", which significantly simplifies design and fabrication process. We laid down the fundamental principle and design methodology using these geometric-phase metasurfaces [Opt. Exp. 20, 14882 (2012)]. It is one of the first papers on this route to numerically demonstrate spin-dependent steering and focusing of light using geometric-phase metasurfaces. We then designed and fabricated metasurfaces of this type to achieve spin-induced manipulation of orbital angular momentum of light [Nano. Lett. 13, 4148 (2013)]. We also considered non-linear responses and we realized nonlinear metasurfaces with continuously controllable phase [Nat. Mater. 14, 607 (2015)] and nonlinear plasmonic metacrystals that exhibit rotational symmetry dependent third harmonic generation [Phys. Rev. Lett. 113, 033901 (2014).]

New techniques: Theory and experimental teams worked together to develop a very precise method to measure the microwave radiation acting on metallic resonant units and showed that the induced radiation force can be two orders of magnitude higher than the usual radiation force due to the reflection on a metallic surface. This method has the unique capability of distinguishing between the direct radiation force and the indirect bolometric component [Phys. Rev. Lett.112, 045504 (2014)]. We have developed a simple and effective shadowing vapor deposition method in the fabrication of chiral metamaterials for the visible range [J. Opt. 15, 072101 (2013)]. The work was selected as in "Lab Talk" of J. of Optics in 2013. There are many routes that can be used to fabricate chiral structures in the nano-scale and our method stands out as being very simple.

New phenomena: It is common textbook knowledge of photon pressure that light (carrying photons with positive linear momentum) will push an object and photons carrying positive angular momentum will rotate an object in the same sense as the incoming photons. We found that by designing systems in which the differential scattering cross sections can be controlled, some special kind of light beams can pull and can turn an object in the opposite sense as the incoming photons. We discovered and optimized many unconventional phenomena such as chirality induced optical pulling force acting on chiral particles [PRA 89, 063825 (2014)], negative optical torque [Sci. Rep. 4, 6386 (2014)], and optimized optical pulling force using "core-shell" structures [Opt. Lett. 39, 2399 (2014)].

Looking forward: PT-symmetric systems can strongly modify scattering and absorption cross sections. As such, the notion of "exceptional points" has attracted a lot of recent attention. As a prelude to a new line of work, we explored the coalescence of exceptional points in PT-symmetric photonic crystals [Phys. Rev. B 92, 235310 (2015)]. Exceptional point physics and topological concepts applied to classical waves will be natural extensions of our current line of work.

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

A natural extension of this CRF project is to explore the application of modern concepts such as topological invariants and parity-time symmetry to the manipulation of light and sound waves. Recent advances in understanding the topological characteristics of momentum space led to the emergence of new classes of electronic materials such as topological insulators and Weyl semimetals. A novel and useful property of this new class of materials is that they can support symmetry protected uninterruptable transport at their edges or surfaces which can be exploited for many advanced applications. It will be interesting to explore the possibility of using topological notions to design artificial wave functional media (metamaterials) that supports robust transport of electromagnetic and acoustic waves that are not compromised by defects or imperfections. It is also interesting to explore the notion of Parity-Time (PT) Symmetry and "exceptional point" and their implications in classical wave transport. In the language of quantum mechanics, "PT" symmetry is about going beyond the usual Hermitian Hamiltonian and explores the consequences of having a non-Hermitian operator. In the language of optics, this is equivalent to considering systems with balanced gain and loss satisfying some specific symmetry requirements. The possibility of realizing new devices and exciting new applications such as loss-induced lasing and perfect absorption enabled by the symmetry breaking transition (exceptional points) should be explored. While most, if not all, of the current attention is focused on non-Hermitian systems that have complex diagonal elements in the Hamiltonian matrix, it is possible to construct classical wave systems in which the governing matrix is real but non-symmetric. The "exceptional point" behavior of such systems and the implications for light and sound waves can be explored.

6.3 Research collaboration achieved *(please give details on the achievement and its relevant impact)*

To achieve the goal of realizing new materials and new structures that can beat natural materials in wave manipulation, we will first conceive such materials or phenomena through intuition and the wave-material interaction would then be simulated using numerical techniques. These two tasks are performed by the theory team. The experimental teams would then make the materials and the phenomena will be measured and characterized. The following are some examples in which the theory-simulation-fabrication-measurement collaboration is crucial for the delivering the new material:

- Low frequency sound absorbers
- Metamaterials with extreme parameters using space-coiling
- Metasurfaces for manipulating the orbital angular momentum of light
- Plasmonic metacrystals and metasurfaces for non-linear effects

We note that some of these materials have immediate application potential.

C.T. Chan's group provides simulation support for the experimental teams, which are essential for the interpretation of measurement results. Examples are the chiral metamaterials of Tam's and Wong's group, various holographic lithography produced samples of Wong's group, the THz's samples of Wen's group for polarization manipulation, and the microwave samples of HB Chan's group.

Collaboration among groups in different institutions take advantage of complementary expertise and equipment available in different institutions facilitate the realization of new structures: Examples are the collaboration between Baptist U group and CityU group in the realization of plasmonic metacrystals and metasurfaces for non-linear effects.

Another example is the collaboration between HKUST groups and the Baptist group to study optical pulling force and negative torque and the design of new methodology to measure optical force. The collaboration between theory and experiment is indispensable in particular for the distinction between heating effect and radiation force.

The CRF team has active international collaboration with the metamaterial laboratory at Birmingham (UK). This collaboration is facilitated by the move of one of our team member (Jensen Li) from CityU to Birmingham.

The group meeting information among different groups that testifies close collaboration can be found in the appendix [Appendix II].

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)

The essence of this proposal is to develop new functional materials and artificial structures to modify the scattering and absorption of electromagnetic waves and acoustic waves. In simple words, we want to design, fabricate and test new man-made materials which can control, confine, scatter or absorb light and sound waves better than what natural materials can do. We put emphasis on simple structures and simple techniques that can be realized more easily. The research output has both academic significance and practical impact. As one example, the team succeeded in designing and making very thin artificial structures that can absorb almost completely low frequency sound. Academically speaking, this is an extremely challenging task and our theory/experiment team jointly solved the problem. The application value is quite obvious and a small start-up company has already been founded by a former student involved in this project. Other amazing effects we have discovered include for example various strategies to use light to pull objects, which was thought to be impossible just a few years ago. Such strategy of using light to pull objects will be particularly useful in the future for the manipulation of small particles which would be otherwise very difficult to control.

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Part C: Research Output

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

(Please attach a copy of the 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.) [See Appendix III for publications]

The Latest Status of Publications				Author(s) *(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 RGC *(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)						
			2015	H. X. He, K. S. Wong*	*Imaging through Thin Scattering Medium by Wavefront Compensation*	2015	No	Yes	Not applicable
		2015		H. M. Su, Y. X. Gao, J. Ma, Y. C. Zhong, W. Y. Tam, C. T. Chan, Kam Sing Wong*	*Multipolar Effects in the Optical Active Second Harmonic Generation from Sawtooth Chiral Metamaterials, Sci. Rep. (under review)*	2015	No	Yes	Not applicable
2015				K. Ding, Z. Q. Zhang, and C.T. Chan*	*Coalescence of Exceptional Points and Phase Diagrams for One-dimensional PT-symmetric Photonic*	2015	Yes	Yes	Yes

					Crystals, Phys. Rev. B 92, 235310 (2015)				
2015				G. X. Li, S. M. Chen, N. Pholchai, B. Reineke, W. H. Wong, Y. B. Pun, K. W. Cheah*, T. Zentgraf, and S. Zhang*	*Continuous Control of the Nonlinearity Phase for Harmonic Generations*, Nat. Mater. 14, 607-612 (2015).	2015	Yes	Yes	Yes
2015				X. Xiao, B. P. Zhou, X. K. Wang, J. W. He, B. Hou, Y. Zhang, and W. J. Wen*	*An Analog of Electrically Induced Transparency via Surface Delocalized modes*, Sci. Rep. 5, (2015).	2015	Yes	Yes	Yes
2015				C. R. Han, and W. Y. Tam*	*Plasmonic Ultra-broadband Polarizers Based on Ag Nano Wire-slit Arrays*, Appl. Phys. Lett. 106, 081102 (2015).	2015	Yes	Yes	Yes
2015				C. R. Han, and W. Y. Tam*	*Chirality from Shadowing Deposited Metallic Nanostructures*, Phot. Nano. Fund. Appl. 13,	2015	Yes	Yes	Yes

					50-57 (2015).				
2015				M. Jie, K. S. Wong, S. Li, Z. Chen, J. Y. Zhou, and Y. C. Zhong*	*Fabrication of Large Area Photonic Crystals with Periodic Defects by One-Step Holographic Lithography*, J Opt Soc Korea 19, 63-68 (2015).	2015	Yes	Yes	Yes
2015				X. Xiao, H. M. Leung, C. T. Chan, and W. J. Wen*	*Manipulation of the Polarization of Terahertz Wave in Subwavelength regime*, Sci. Rep. 5 (2015).	2015	Yes	Yes	Yes
2015				S. W. Xiao, G. C. Ma, Y. Li, Z. Y. Yang, P. Sheng*	*Active Control of Membrane-type Acoustic Metamaterial by Electric Field*, Appl. Phys. Lett. 106, 091904 (2015)	2015	Yes	Yes	Yes
2014				X. Xiao, Y. Liu, and W. J. Wen*	*Ruderman–Kittel–Kasuya–Yosida Interaction in Silicene*, J. Phys.	2015	Yes	Yes	Yes

					Condens. Matter 26, 266001 (2014).				
2014				N. Wang*, W. L. Lu, J. Ng, and Z. F. Lin	*Optimized Optical "Tractor Beam" for Core–shell Nanoparticles*, Opt. Lett. 39, 2399-2402 (2014).	2015	Yes	Yes	Yes
2014				X. Wang, W. S. Gao, J. Hung, and W. Y. Tam*	*Optical Activities of Large-area SU8 Microspirals Fabricated by Multibeam Holographic Lithography*, Appl. Opt. 53, 2425-2430 (2014).	2015	Yes	Yes	Yes
2014				S. M. Chen, G. X. Li, F. Zeuner, W. H. Wong, Y. B. Pun, T. Zentgraf*, K. W. Cheah*, and S. Zhang*	*Symmetry-selective Third-harmonic Generation from Pasmonic Metacrystals*, Phys. Rev. Lett. 113, 033901 (2014).	2015	Yes	Yes	Yes
2014				Y. Lai*, J. Ng, and C. T. Chan*	*Creating Illusion Effects Using Transformation Optics*, in Transformation	2015	Yes	Yes	Yes

					Electromagnetics and Metamaterials, pp. 139-165. Springer London, 2014.				
2014				J. Chen, J. Ng*, K. Ding, K. H. Fung, Z. F. Lin, and C. T. Chan*	*Negative Optical Torque*, Sci. Rep. 4 (2014).	2015	Yes	Yes	Yes
2014				K. Ding, J. Ng*, L. Zhou, and C. T. Chan*	*Realization of Optical Pulling Forces Using Chirality*, Phys. Rev. A 89, 063825 (2014).	2015	Yes	Yes	Yes
2014				G. C. Ma, M. Yang*, S. W. Xiao, Z. Y. Yang, and P. Sheng*	*Acoustic Metasurface with Hybrid Resonances*, Nat. Mater. 13, 873 (2014)	2015	Yes	Yes	Yes
2014				M. Yang, G. C. Ma, Y. Wu, Z. Y. Yang, and P. Sheng*	*Homogenization Scheme for Acoustic Metamaterials*, Phys. Rev. B89, 064309 (2014)	2015	Yes	Yes	Yes
2014				Z. Marcet, Z. H. Hang, S. B. Wang, J. Ng, C. T. Chan and H. B. Chan*	*Measurement of Enhanced Radiation Force on a Parallel Metallic-plate System in the Microwave Regime*,	2015	Yes	Yes	Yes

					Phys. Rev. Lett. 112, 045504 (2014)				
2014				H. M. Leung, C. R. Han, Y. H. Li, C.T. Chan and W. Y. Tam*	*Modelling Quasi-3D Chiral Metamaterials Fabricated by Shadowing Vapor Deposition*, J. Opt. 16, 015102 (2014)	2013	No	Yes	Yes
2013				Z. N. Yue, Y. F. Cheung, H. W. Choi, Z. J. Zhao, B. Z. Tang, and K. S. Wong*	*Hybrid GaN/Organic White Light Emitters with Aggregation Induced Emission Organic Molecule*, Opt Mater Express 3, 1906-1911 (2013).	2015	Yes	Yes	Yes
2013				J. Y. Zhou*, Y. K. Liu, S. C. Wang, Y. Y. Li, L. Y. Song, X. S. Xie, M. N. Feng, Z. M. Xiao, S. Z. Deng, J. T. Li, K. S. Wong, and F. Krauss*	*Efficient Colour Routing with a Dispersion-controlled Waveguide Array*, Light. Sci. Appl. 2, e52; doi :10.1038/lsa.2013.8 (2013)	2013	No	Yes	Yes
2013				S. B. Wang*, H. H. Zheng, J. J. Xiao, Z. F. Lin,	*Fast Multiple Boundary Element Method for*	2013	No	Yes	Yes

				and C. T. Chan*	*Three Dimensional Electromagnetic Scattering Problem*, Int. J. Comp. Mat. Sci. Eng. 01, 1250038 (2013)				
2013				S. M. Chen, G. X. Li, D. Y. Lei* and K. W. Cheah*	*Efficient Energy Exchange between Plasmon and Cavity Modes via Rabi-analogue Splitting in a Hybrid Plasmonic Nanocavity*, Nanoscale 5, 9129-9133 (2013)	2013	No	Yes	Yes
2013				B. Hou and W. J. Wen*	*Enhanced Transmission of Acoustic Waves Through Subwavelength Holes in Hard Plates*, Book Chapter of "Modeling and Measurement Methods for Acoustic Waves and for	2013	No	Yes	Yes

					Acoustic Microdevices", edited by M. G. Beghi (2013)				
2013				C. R. Han, H. M. Leung and W. Y. Tam*	*Chiral Metamaterials by Shadowing Vapor Deposition*, J. Opt. 15, 072101 (2013)	2013	No	Yes	Yes
2013				G. X. Li, M. Kang, S. M. Chen, S. Zhang, Edwin Y. B. Pun, K. W. Cheah, and J. Li*	*Spin-Enabled Plasmonic Metasurfaces for Manipulating Orbital Angular Momentum of Light*, Nano Lett. 13, 4148−4151 (2013)	2013	No	Yes	Yes
2013				S. M. Chen, W. H. Wong, Y. P. Pun, K. W. Cheah*, G. X. Li*	*Surface Plasmon-enhanced Third Harmonic Generation from Gold–polymer Hybrid Plasmonic Crystal*, Adv. Optical Materials 1 (7), 522 (2013)	2013	No	Yes	Yes
2013				M. Yang*, Z. Y. Yang and P. Sheng	*Full-band Exact Homogenization of One-dimensional Elastic*	2013	No	Yes	Yes

					Metamaterials, Proceedings of Meetings on Acoustics, Vol. 19, 065016 (2013)				
2013				G. C. Ma*, M. Yang, Z. Y. Yang*, and P. Sheng	*Low-frequency Narrow-band Acoustic Filter with Large Orifice,* Appl. Phys. Lett. 103, 011903 (2013)	2013	No	Yes	Yes
2013				M. Yang, G. C. Ma, Z. Y. Yang, and P. Sheng*	*Coupled Membranes with Doubly Negative Mass Density and Bulk Modulus,* Phys. Rev. Lett. 110, 134301 (2013)	2013	No	Yes	Yes
2013				Andrei S. Susha, Andrey A. Lutich, C. M. Liu, H. Xu, R. Q. Zhang, Y. C. Zhong, K. S. Wong, S. H. Yang, and Andrey L. Rogach*	*Comparative Optical Study of Colloidal Anatase Titania Nanorods and Atomically Thin Wires,* Nanoscale 5, 1465 (2013)	2013	No	Yes	Yes

2013				Marta M. Mroz*, G. Sforazzini, Y. C. Zhong, K. S. Wong, Harry L. Anderson, G. Lanzani and J. Cabanillas-Gonzalez	*Amplified Spontaneous Emission in Conjugated Polyrotaxanes under Quasi-cw Pumping*, Adv. Mater. 25, 4347 (2013)	2013	No	Yes	Yes
2013				X. Xiao, S. Li, K. T. Law, B. Hou, C. T. Chan and W. J. Wen*	*Thermal Coherence Properties of Topological Insulator Slabs in Time-reversal Symmetry Breaking Fields*, Phys. Rev. B 87, 205424 (2013)	2013	No	Yes	Yes
2013				X. Xiao and W. J. Wen*	*Optical Conductivities and Signatures of Topological Insulators with Hexagonal Warping*, Phys. Rev. B 88, 045442 (2013)	2013	No	Yes	Yes
2013				Z. X. Liang, T. H. Feng, S. K. Lok, F. Liu, K. B. Ng, C. H. Chan, J. J. Wang, S. H.	*Space-coiling Metamaterials with Double Negativity and*	2013	No	Yes	Yes

				Han, S. Y. Lee and J. Li*	*Conical Dispersion*, Sci. Rep. 3, 1614 (2013)				
2013				T. H. Feng, F. Liu, W. Y. Tam and J. Li*	*Effective Parameters Retrieval for Complex Metamaterials with Low Symmetries*, EuroPhy. Lett. 102, 18003 (2013)	2013	No	Yes	Yes
2013				X. H. Hu*, J. Yang, J. Zi*, C. T. Chan and K. M. Ho	*Experimental Observation of Negative Effective Gravity in Water Waves*, Sci. Rep. 3, 1916 (2013)	2013	No	Yes	Yes
2013				S. B. Wang and C. T. Chan*	*Microwave-induced Elastic Deformation of a Metallic Thin Film*, J. Phys. D: Appl. Phys. 46, 395104 (2013)	2013	No	Yes	Yes
2013				Y. S. Ding*, C. T. Chan* and R. P. Wang	*Optical Waves in a Gradient Negative-index Lens of a Half-infinite Length*, Sci. Rep. 3, 2954	2013	No	Yes	Yes

					(2013)				
2012				Z. X. Liang and J. Li*	*Extreme Acoustic Metamaterial by Coiling Up Space*, Phys. Rev. Lett. 108, 114301 (2012)	2013	No	Yes	No
2012				M. Xiao, X. Q. Huang, J. W. Dong, and C. T. Chan*	*On the Time Evolution of the Cloaking Effect of a Metamaterial Slab*, Opt. Lett 37 (22), 4594 (2012)	2013	No	Yes	Yes
2012				W. S. Gao, C. Y. Ng, H. M. Leung, Y. H. Li, H. Chen and W. Y. Tam*	*Circular Dichroism in Single Layered Gold Sawtooth Gratings*, J. Opt. Soc. Am. B 29, 3021-3026 (2012)	2013	No	Yes	Yes
2012				C. R. Han and W. Y. Tam*	*Graded Photonic Crystals by Optical Interference Holography*, J. Opt. 14, 085104 (2012)	2013	No	Yes	Yes
2012				M. Kang, T. H. Feng, H. T. Wang, and J. Li*	*Wave Front Engineering from an Array of*	2013	No	Yes	No

					Thin Aperture Antennas, Opt. Express 20 (14), 15882 (2012)				
2012				J. Zhou*, L. Jin and Edwin Y. B. Pun	*Tunable Multichannel Nonreciprocal Perfect Absorber Based on Resonant Absorption*, Opt. Lett 37 (13), 2613 (2012)	2013	No	Yes	Yes
2012				X. Xiao, Y. Li, B. Hou, B. Zhou, and W.J. Wen*	*Subwavelength Polarization Rotators via Double-layer Metal Hole Arrays,* Opt. Lett. 37 (17), 3594 (2012)	2013	No	Yes	Yes
2012				M. C. Tam, A M. C. Ng, A. B. Djurišić and K. S. Wong*	*Correlation of Quantum Efficiency and Photoluminescence Lifetime of ZnO Tetrapods Grown at Different Temperatures,* J. Appl. Phys. 112, 023515 (2012)	2013	No	Yes	Yes

2012				J. Mei, G. C. Ma, M. Yang, Z. Y. Yang, W. J. Wen and P. Sheng *	*Dark Acoustic Metamaterials as Super Absorbers for Low-frequency Sound*, Nat. Commun. 3, 756 (2012)	2013	No	Yes	Yes
2012				S. M. Chen, G. X. Li, W. H. Wong, Edwin Y. B. Pun and K. W. Cheah*	*Sharp Plasmonic Resonance on Gold Gratings in Amplitude and Phase Domains*, Appl. Opt. 51 (36), 8563 (2012)	2013	No	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 conference abstract - see Appendix IV)*

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 RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
April/2015/ Dubrovnik, Croatia	Membrane-type Elastic Metamaterials for Noise Abatement Applications (panel talk)	Noise and Vibration – Emerging Technologies	2015	Yes	Yes	Yes
December/ 2014/ Okinawa, Japan	Robust Interface States in Two-dimensional Photonic Crystals (invited talk)	The 9th General Meeting of Asian Consortium on Computational Materials Science	2015	Yes	Yes	No

November/ 2014/Shanghai, China	Meta-materials with Zero Refractive Index (invited talk)	Asia Communications and Photonics Conference Shanghai	2015	Yes	Yes	Yes
October/2014/Beijing, China	Unusual Optical Force and Torque Acting on Plasmonic Objects (invited talk)	SPIE Photonics Asia 2014 – Plasmonics	2015	Yes	Yes	No
August/2014/Switzerland	Circular Polarized Second Harmonic Generation in Single-layered Gold Sawtooth Structures	6th EPS-QEOD Europhoton Conference	2015	Yes	Yes	Yes
August/2014/US	Chirality Enables Unusual Optical Force (Invited talk)	Plasmonics: Metallic Nanostructures and Their Optical Properties XI	2015	Yes	Yes	No
August/2014/ Guangzhou, China	Angle Dependent Effective Medium Theory for 2D Photonic Crystals (invited talk)	PIERS 2015	2015	Yes	Yes	No
August/2014/ Guangzhou, China	Pushing and Pulling Chiral Particles with Light (invited talk)	PIERS 2015	2015	Yes	Yes	No
July/2014/ Changchun, China	Using Light to Push and Pull and Rotate (invited talk)	Light Conference -International Conference on Micro/Nano Optical Engineering	2015	Yes	Yes	No
June/2014/ Singapore	Non-linear Optical Properties of Plasmonic Devices	The 8th OCPA International Conference on Physics Education and Frontier Physics	2015	Yes	Yes	No
May/2014/ Shanghai, China	Zak Phase and Gap Inversion in Periodic Acoustic Systems (Plenary talk)	The 2nd International Conference on. Phononics and Thermal Energy Science	2015	Yes	Yes	No

May/2014/ Shanghai, China	Deterministic Formation of Interface States in Some Two-Dimensional Photonic Crystals with Conical Dispersions (invited talk)	The 11th International Symposium on Photonic and Electromagnetic Crystal Structures	2015	Yes	Yes	No
May/2014/ The Netherlands	The Moving Contact Line in Immiscible Flow: Theory and Experiment (Keynote talk)	First International Conference on Micro & Nanofluidics: Fundamentals and Applications	2015	Yes	Yes	No
January/2014/Kobe, Japan	Non-linear Optical Properties of Plasmonic Devices (invited talk)	8th Asian Conference on Ultrafast Phenomena	2015	Yes	Yes	No
October/ 2013/ Taipei	Optical Force and Stress (Invited talk)	International Conference of Applied Sciences 2013 - RCAS, Academia Sinica	2013	No	Yes	No
September/ 2013/ Innsbruck, Austria	Doubly Negative Acoustic Metamaterial with Coupled Membrane Resonator (invited talk)	Inter. Noise 2013	2013	No	Yes	No
August/ 2013/ San Diego	Dirac Cone Dispersions in Photonic Crystals and Their Implications (Invited talk)	SPIE 2013	2013	No	Yes	No
July/2013/ Singapore	New Effective Medium Theories for Electro-restrictive Tensors and for Classification of Band and Gaps (Invited talk)	ICMAT 2013	2013	No	Yes	No
June/2013/ Singapore	Interface States in Photonic Crystals with Dirac Cone Dispersions (Invited talk)	9th Singapore-China Joint Symposium on Research Frontiers in Physics	2013	No	Yes	No

June/ 2013 San Jose	Robust Interface States in Two Dimensional Photonic Crystals with Dirac Cone Dispersions (Invited talk)	CLEO 2013	2013	No	Yes	Yes
June/2013/ Egypt	Dirac Cone Dispersion and Its Implications in Phononics (Invited talk)	PHONONICS 2013: 2nd International Conference on Phononic Crystals/Meta materials, Phonon Transport and Optomechanics	2013	No	Yes	No
June/2013/ Montréal, Canada	Acoustic Double Negativity with Coupled-Membrane Metamaterial (invited talk)	21st International Congress on Acoustics	2013	No	Yes	Yes
June/2013/ Montréal, Canada	Full-band Exact Homogenization of One-dimensional Elastic Metamaterials (invited talk)	21st International Congress on Acoustics	2013	No	Yes	Yes
June/2013/ Sharm El-Sheikh, Egypt	Dark Acoustic Metamaterials (plenary talk)	Second International Conference on Phononic Crystals/Meta materials, Phonon Transport and Optomechanics	2013	No	Yes	No
June/2013/ Hong Kong	Non-linear Optical Response of Au Circular Split Ring Nanostructure	The 16th Conference of The Physical Society of Hong Kong	2013	No	Yes	No
June/2013/ South Korea	Fabrication of 2- and 3-dimensional Photonic Crystals by Single Beam Holographic Lithography (invited talk)	Collaborative Conference on 3D & Materials Research	2013	No	Yes	No

May/2013 /Singapore	Membrane-Type Acoustic Metamaterials: Reflection and Absorption of Low Frequency Sound (keynote talk)	2013 International Congress on Ultrasonics	2013	No	Yes	No
May/2013/ Hong Kong	Fabrication of two- and three-dimensional Photonic Crystals using Holographic Lithography and Spatial Light Modulator for Phase Control (Invited talk)	The 7th International Conference on Nanophotonics and the 3rd Conference on Advanced in Optoelectronics and micro/Nano Optics	2013	No	Yes	Yes
March/ 2013/ Taipei	Optical Force in Parallel-plate Metamaterial	Progress In Electromagnetics Research Symposium 2013	2013	No	Yes	No
January/ 2013/ Singapore	Optical Force and Stress (Invited talk)	IEEE INEC International Nano-electronics Conference2013	2013	No	Yes	No
December/ 2012/ Singapore	Dirac Cone Dispersion in Photonic Systems and Zero Refractive Index (Invited talk)	PGC Photonic Global Conference 2012	2012	No	Yes	No
December/ 2012/ Boston	Dirac Dispersion in Photonic Crystals and Zero Refractive Index (Invited talk)	MRS 2012 Boston, Symposium BB	2012	No	Yes	No
October/ 2012/ Nanjing	Optical Force and Stress (Invited talk)	2012 International Workshop on Metamaterials	2012	No	Yes	No

September/ 2012/St. Petersburg, Russia	Acoustic Metamaterials through Coiling up Space	Metamaterials 2012: The Sixth International Congress on Advanced Electromagnetic Materials in Microwave and Optics	2015	Yes	Yes	No
September/ 2012/ Marseille, France	Dark Acoustic Metamaterials as Super Absorbers of Low Frequency Sound (invited talk)	9th International Conference on Electrical, Transport and Optical Properties of Inhomogeneous Media (ETOPIM9)	2013	No	Yes	No
August/ 2012/ New York	Light Weight Composite Thin Panels for Broad Band Sound Attenuation in the 50-1000 Hz Regime (invited talk)	Inter. Noise	2013	No	Yes	No
July/2012/ St Petersburg, Russia	Dark Acoustic Metamaterials as Super Absorbers of Low Frequency Sound (invited talk)	International Summer School-Conference on Advanced Problems in Mechanics-2012	2013	No	Yes	No
June/2012/ New Mexico	Dirac Cone Dispersions in Photonic and Phononic Systems (Invited talk)	PECS X: 10th International Symposium on photonic and Electromagnetic Structures	2013	No	Yes	No
June/2012/ Japan	Novel Plasmonic Material and Devices	ICOOPMA 2012	2013	No	Yes	No
February/ 2012/ Boston	Experimental Observation of Strong Microwave Induced Force in Parallel-plate Metallic Cavity	APS March Meeting	2013	No	Yes,	No

10. ***Student(s) trained*** (please attach a copy of the title page of the thesis - See Appendix V)

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Chen Binling	MPhil in Physics	September 2011	Date of graduation: August 2014
Chen Shumei	PhD in Physics	September 2011	Date of graduation: August 2014
Deng Junhong	PhD in Physics	September 2012	Expected date of graduation: August 2016
Fatemeh Hosseini	PhD in Physics	January 2013	Expected date of graduation: January 2016
Fu Caixing	PhD in Physics	September 2014	Expected date of graduation: August 2018
Gary Ka Long Ng	MPhil Physics	September 2013	Expected date of graduation: August, 2016
Han Chunrui	PhD in Nano Science and Technology Program	September 2010	Date of Graduation: August 2014
Hung Jenny	PhD in Nano Science and Technology Program	September 2006	Date of Graduation: August 2013
Leung Ho Ming Dick	PhD in Physics	September 2009	Expected date of graduation: August 2017
Ma Guancong	PhD in Physics	September 2007	Date of graduation: August 2012
Meng Chong	PhD in Physics	September 2013	Expected date of graduation: August 2016
Sun Ke	PhD in Nano Science and Technology Program	September 2004	Date of graduation: August 2012
Wang Shubo	PhD in Nano Science and Technology Program	September 2009	Date of graduation: August, 2013
Xiao Meng	PhD in Physics	September 2010	Date of graduation: August, 2014
Xiao Songwen	PhD in Physics	September 2012	Expected date of graduation: August, 2016
Xiao Xiao	PhD in Physics	September 2007	Date of graduation: August 2012
Yang Min	PhD in Physics	September 2010	Date of graduation: August, 2014
Ye Piao	MPhil in Physics	September 2013	Date of graduation: August, 2015

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

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Prize:
Ping Sheng, C.T. Chan and J. Yang were the winner of the 2013 Brillouin Medal from the International Phononics Society for their work on acoustic metamaterial.

Patents granted:
Vibration Energy Absorption Devices (US Patent 8,960,365)

Patent applications:
The following applications are under review by US Patents and Trademarks Office

(1) Acoustic Metamaterial with Simultaneously Negative Effective Mass Density and Bulk Modulus (TTC.PA.0644)
(2) Sound Attenuation Structures II (TTC.PA.0667)
(3) Extraordinary Acoustic Absorption Induced by Anti-resonance (TTC.PA.0685)
(4) Membrane-type Acoustic Metamaterials Controlled by Electric or Magnetic Fields (TTC.PA.0701)
(5) Damped sound shield (TTC.PA.0784)
(6) Elastic Metamaterials with Independent Monopole and Dipole Resonant Structures (TTC.PA.0850)

A patent has been licensed to Acoustic Metamaterials, Inc. for commercialization using our research outcomes.

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Project Coordinator

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