RESEARCH GRANTS COUNCIL
AREAS OF EXCELLENCE (AoE) SCHEME

Completion Report on Funded Project

Project start date: *November 1, 2013*
Project completion date: *October 31, 2021*

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1. Project Title: Novel Wave Functional Materials for Manipulating Light and Sound

2. Names and Academic Affiliations of Project Team Members#

Project team member	Name / Post	Unit / Department / Institution	Average number of hours per week spent on this project in the whole project period
Project Coordinator (PC)	C.T. Chan / Chair Professor	Physics / HKUST	24
Co-Principal Investigator(s)	K.W. Cheah / Chair Professor	Physics / HKBU	3
	Aaron Ho / Professor	Biomedical Engineering / CUHK	4
	Edwin Pun / Chair Professor	Electronic Engineering / CityU	4
	P. Sheng / Professor Emeritus *	Physics / HKUST	5.5
	Penger Tong / Chair Professor	Physics / HKUST	4
Co-Investigator(s)	H.B. Chan / Professor	Physics / HKUST	6
	K.H. Fung / Assistant Professor	Applied Physics / PolyU	5

	S.K. Kong / Professor Emeritus	Life Sciences / CUHK	4.3
	Randolph Leung / Associate Professor	Mechanical Engineering / PolyU	6
	Jack Ng / Associate Professor	Physics / SUSTech	6.25
	Daniel Ong / Professor	Physics / CUHK	4.5
	H.L. Tam / Research Fellow**	Physics / HKBU	5
	W.Y. Tam / Professor Emeritus	Physics / HKUST	16
	W.J. Wen / Professor Emeritus***	Physics / HKUST	2.5
	K.S. Wong / Professor	Physics / HKUST	11
	J.B. Xu Professor	Electronic Engineering / CUHK	6.5
	Jason Yang / Professor	Physics / HKUST	8
Collaborators	Jensen Li / Professor	Physics / HKUST	N.A.
	Hui Liu / Professor	Physics / Nanjing University	N.A.
	Steven G. Louie / Professor of Physics	Physics / UC Berkeley	N.A.
	Stefan Maier / Professor of Nanophotonics	Physics / Imperial College London	N.A.
	John Pendry / Chair Professor in Theoretical Solid State Physics	Physics / Imperial College London	N.A.
	Shining Zhu / Professor	Physics / Nanjing University	N.A.

\# *Please highlight the approved changes in the project team composition and quote the date when the UGC/RGC granted approval of such changes. For changes in the project team composition, please submit a separate request, together with the justification and the curriculum vitae of the new member(s), to the RGC three months prior to the intended effective date of the change.*

* P. Sheng retired from HKUST with effect from 1 July, 2022. He is now a Professor Emeritus.
**The title of H.L. Tam has been changed from Research Associate to Research Fellow.
*** W.J. Wen retired from HKUST with effect from July 1, 2021. He continued to be a Co-I for the remaining period of the AoE project. The notification letter has been sent to RGC dated June 10, 2021.

Project team confirm that the number of hours in the final report refers to the average number of hours per week spent on this project in the whole project period and hence it can be slightly different from those reported in the 7th progress report.

3. Project Objectives

Summary of objectives addressed/achieved:

Objectives*	Percentage achieved	Remarks**
1. Design, fabricate and characterize new materials that can manipulate light and sound in ways not known before.	1. 100%	1.
2. Develop new and improve existing theoretical, numerical and fabrication techniques for the realization of these new materials.	2. 100%	2.
3. Use these wave functional materials to achieve interesting and unusual effects that are not possible with natural materials. Example effects include strongly modified scattering cross or absorption section, unusual wave guiding and confinement, unusual values of refractive indices, strongly modified density of states and enhanced local field.	3. 100%	3.
4. Explore and realize potential applications of these new materials.	4. 100%	4.

* *Please highlight the approved changes in objectives and quote the date when the UGC/RGC granted approval of such changes.*

** *Please provide reasons for significantly slower rate of progress than originally planned.*

6. Research Highlights and Outputs

6.1 What are the most exciting research accomplishments of the project?
(Please list five or more of the team's best research accomplishments, such as journal and conference papers, software codes, research infrastructure, etc. For each item, please clearly justify how it has achieved international excellence (e.g. best paper award, invited presentation, citations, product licensed to industry, etc.))

The team has made a collective effort to conceive, design, fabricate and characterize novel wave functional materials and realize their potential to manipulate light and sound. We have published our findings in high-impact journals such as Science, Nature, Nature Physics, Nature Materials, Nature Photonics, Nature Communications, Science Advances, PRX, PRL and PNAS. Our works have been highlighted in journals and magazines and chosen as editors' highlights and cover pages of journals. Members have been invited to give plenary and keynote talks in major international conferences related to metamaterials and optics. Five of our research accomplishments are summarized in the following.

Acoustic metamaterials based on local resonances
An important breakthrough we have made is the broadband absorption functionality of acoustic metamaterials incorporating local resonances, achieved through the optimal design strategy that is integrated with the causality principle. That breakthrough led to a series of seminal and highly cited papers in the field, including, for example, G.C. Ma, P. Sheng, "Acoustic Metamaterials: from Local Resonances to Broad Horizons", Sci. Adv. 2:e1501595 (2016) [>900 citations]; G.C. Ma, M. Yang, S.W. Xiao, Z.Y. Yang, P. Sheng, "Acoustic Metasurface with Hybrid Resonances", Nat. Mater. 13, 873-878 (2014) [>800 citations]; and M. Yang, S.Y. Chen, C. X. Fu, P. Sheng, "Optimal Sound-absorbing Structures", Mater. Horiz. 4, 673 (2017) [>250 citations]. This line of work has attracted worldwide attention from academia and industry, and enabled the commercialization of the acoustic metamaterials (see Section 6.7) through a company called Acoustic Metamaterials Group (www.metacoust.com) founded by members of Ping Sheng's group. Details of the design paradigm of these acoustic metamaterials can be found in "An Integration Strategy for Acoustic Metamaterials to Achieve Absorption by Design", M. Yang, P. Sheng, Appl. Sci., 8, 1247 (2018); and "Acoustic Metamaterials", J. Li, X.H. Wen, P. Sheng, J. Appl. Phys. 129, 171103 (2021). Ping Sheng and his group members have been invited to give numerous invited, keynote and plenary talks in international conferences.

Topological metamaterials and photonic/phononic crystals
We have conceptually conceived, numerically simulated and experimentally realized many metamaterials, photonic crystals and plasmonic clusters endowed with novel physical properties not found in nature. Particularly worth mentioning is the pioneering work of using photonic and acoustic systems to realize topological materials and to manifest topological effects in light and sound. The application of topological concepts has dominated condensed matter research in the past two decades. Such ideas also apply to light and sound, and we found that topological effects can also be realized and manifested in metamaterials, photonic crystals and phononic crystals in their own unique way. Many highly cited papers describing these findings have been published in high-impact journals, and we have also presented them at numerous invited, keynote and plenary talks in conferences.

The initial effort in the area focused on finding the photonic and acoustic analogue of electronic topological insulators. There are many challenges. For example, some degeneracies required for realizing topological effects (e.g. Kramer's degeneracy) in electronic materials are intrinsically Fermionic degeneracies and do not exist in classical waves, which are bosonic in nature. Acoustic waves are even more challenging, as they lack the spin degrees of freedom. Acoustic waves also do not respond to magnetic fields, and hence the key external parameter (B field) that can generate Chern numbers (in 2D systems) cannot be used. We used the structural degree of freedom in metamaterials to overcome these issues. For example, we successfully demonstrated band inversion in periodic acoustic systems [see, for example, M. Xiao, G.C. Ma, Z.Y. Yang, P. Sheng, Z.Q. Zhang, C.T. Chan, "Geometric Phase and Band Inversion in Periodic Acoustic Systems", Nat. Phys. 11, 240-244 (2015) [> 450 citations]]. Band inversion is a fundamental mechanism underlying topological effects in periodic systems. We realized the notion of a photonic topological insulator in a waveguide system using a non-bianisotropic and non-resonant metamaterial. This is the photonic analogue of a time reversal-invariant topological quantum spin Hall insulator [W.J. Chen, S.J. Jiang, X.D. Chen, B.C. Zhu, L. Zhou, J.W. Dong, C.T. Chan, "Experimental Realization of Photonic Topological Insulator in a Uniaxial Metacrystal Waveguide", Nat. Commun. 5, 5782 (2015) [> 450 citations]]. Following the initial successes, we pushed the boundaries of the topological concept to go beyond finding analogues of electronic topological matter. We focused on concepts and notions and phenomena unique to light and sound. Owing to the spin-1 nature of photons and the specific form of Maxwell's equations, electromagnetic waves possess unique topological properties and intrinsic symmetries which can ramify new photonic topological phases or singularities not found in electric materials. One of the cornerstone concepts of topological theory is the so-called bulk boundary correspondence, which is a mathematically abstract concept that links the bulk topological invariant to surface properties. We showed a rigorous relation between the surface impedance of photonic crystals and their bulk properties through the geometrical phases of the bulk bands, which can be used to determine the existence of interface states or lack thereof. Our results provide new insights into the relationship between surface scattering properties, bulk band properties and the formation of interface states in the context of electromagnetic waves through the familiar notion of surface impedance, rather than mathematically abstract ideas [see, e.g., M. Xiao, Z.Q. Zhang, C.T. Chan, "Surface Impedance and Bulk Band Geometric Phases in One-dimensional Systems", Phys. Rev. X 4, 021017 (2014) [> 400 citations]]. We also showed that we can use structure alone to induce the effect of gauge fields [M. Xiao, W.J. Chen, W.Y. He, C.T. Chan, "Synthetic Gauge Flux and Weyl Points in Acoustic Systems", Nat. Phys. 11, 920 (2016) [> 350 citations]].

We are now pushing the concept of topological photonic and acoustic metamaterials into new frontiers. Conventional topological materials are classified using integers, but new approaches are available in which parity-time (PT)-symmetric topological materials can be classified using matrix-like entities instead of integers, leading to a deeper understanding and the prediction of other novel phenomena. Such approaches are called "non-Abelian", as matrix operations do not commute. These non-Abelian approaches are particularly useful for multi-gap topological-phase bosonic and classical wave systems, as the frequencies useful for technology in these systems can span all bandgaps, as opposed to electronic materials where only phenomena near the Fermi energy are useful. This opens a new direction in topological material research, and we demonstrated such systems recently in electromagnetics and acoustics. The results are published recently in high-impact journals [Q. Guo, T. Jiang, R.-Y. Zhang, L. Zhang, Z.-Q. Zhang, B. Yang, S. Zhang, C. T. Chan, "Experimental Observation of Non-Abelian Topological Charges and Edge States", Nature 594, 195 (2021); Z.-G. Chen, R.-Y. Zhang, C. T. Chan, and G. Ma, "Classical Non-Abelian Braiding of Acoustic Modes", Nat. Phys. 18, 179 (2022); Y. Chen, R.-Y. Zhang, Z. Xiong, Z. H. Hang, J. Li, J. Q. Shen, and C. T. Chan, "Non-Abelian Gauge Field Optics", Nat. Commun. 10, 3125 (2019); and T.S. Jiang, Q. Guo, R.Y. Zhang, Z.Q. Zhang, B. Yang, C.T. Chan, "Four-band Non-Abelian Topological Insulator and Its Experimental Realization", Nat. Commun. 12 (1), 1-9 (2021)].

More of our breakthroughs are discussed in an invited review [G. Ma, M. Xiao, C.T. Chan, "Topological Phases in Acoustic and Mechanical Systems," Nat. Rev. Phys. 1, 281 (2019) [> 350 citations]]. This review was included in *Nature's* collection of "40 Years of Quantum Hall Effect" https://www.nature.com/nature/collections.

Non-Hermitian physics and high-order exceptional points realized using metacrystals and coupled resonator systems

In the past decade, interest has grown rapidly in studying systems described by non-Hermitian Hamiltonians, which better describe non-conservative systems in nature. In optics, such systems can be realized when loss and/or gain is incorporated. Of particular interest is the existence of "exceptional points" (EPs) in such systems. EPs are singularities in the parameter space where two or more eigenvalues and their eigenvectors coalesce simultaneously. Near the EPs, the system is highly sensitive to the environment, leading to potential niche applications such as sensors and lasing. Previously, the literature would focus on "order-2" EPs, where two eigenvalues and their eigenvectors coalesce. We explored and successfully realized higher-order EPs, in which more than two eigenvalues and their eigenvectors coalesce simultaneously. Higher order EPs are much more difficult to realize. As an analogy, observing an order-2 EP is like encountering a 2-car collision, while observing an order-N EP is like encountering an N-car collision. Some important results in this area are published in high-impact journals [see, for example, W. Tang, X. Jiang, K. Ding, Y.-X. Xiao, Z.Q. Zhang, C. T. Chan, and G. Ma, "Exceptional Nexus with a Hybrid Topological Invariant", Science 370, 1077 (2020); S. Wang, B. Hou, W. Lu, Y. Chen, Z. Q. Zhang, and C. T. Chan, "Arbitrary Order Exceptional Point Induced by Photonic Spin-Orbit Interaction in Coupled Resonators", Nat. Commun. 10, 832 (2019); K. Ding, G. Ma, M. Xiao, Z. Q. Zhang, and C. T. Chan, "Emergence, Coalescence, and Topological Properties of Multiple Exceptional Points and Their Experimental Realization", Phys. Rev. X 6, 021007 (2016); K. Ding, G. Ma, Z. Q. Zhang, and C. T. Chan, "Experimental Demonstration of an Anisotropic Exceptional Point", Phys. Rev. Lett. 121, 085702 (2018); X.L. Zhang, S. Wang, B. Hou, and C. T. Chan, "Dynamically Encircling Exceptional Points: In Situ Control of Encircling Loops and the Role of the Starting Point", Phys. Rev. X 8, 021066 (2018); and X. Li, Y. Liu, Z. Lin, J. Ng, and C. T. Chan, "Non-Hermitian Physics for Optical Manipulation Uncovers Inherent Instability of Large Clusters", Nat. Commun. 12, 6597 (2021)].

Advanced optoelectronics, photonics and photovoltaics enabled by the synergistic effect nanomaterials and metamaterials

The wave manipulation properties of conventional photonic crystals and metamaterials are derived from the structural details within the unit cell of these man-made materials. This distinguishes them from natural materials where the optical properties are derived from the electronic properties of the materials. In metamaterials, the electronic properties appear as macroscopic constitutive parameters. But we can combine the unique electronic properties of some new nanomaterials with micro/meso scale structures to achieve unique wave manipulation effects. Of particular importance are 2D materials such as graphene, which possess optical properties that are distinctly different from bulk 3D materials. Their optical properties can be controlled more easily through morphology change or by imposing external fields. Combining atomic-scale response with wavelength-scale resonance, these materials with new structures have interesting properties that can be used in a new generation of sensors featuring ultra-high sensitivity and in energy-harvesting devices.

Using this approach, advances in sensor technology have been demonstrated and resulted in a series of highly cited papers [see, for example, X.M. Wang, Z.Z. Cheng, K. Xu, H.K. Tsang, J.B. Xu, "High-responsivity Graphene/silicon-heterostructure Waveguide Photodetectors", Nat. Photonics 7, 888 (2014) [> 700 citations]; X.M. Li, L. Tao, Z.F. Chen, H. Fang, X.S. Li, X.R. Wang, J.B. Xu, H.W. Zhu, "Graphene and Related Two-dimensional Materials: Structure-property Relationships for Electronics and Optoelectronics", Appl. Phys. Rev. 4, 021306 (2017) [> 480 citations]; L. Ye, H. Li, Z.F. Chen, J.B. Xu, "Near-infrared Photodetector Based on MoS_2/Black Phosphorus Heterojunction", ACS Photonics 3, 692-699 (2016) [> 400 citations]; and Z.F. Chen, Z. Wang, X.M. Li*, Y.X. Lin, N.Q. Luo, M.Z. Long, N. Zhao, J.B. Xu, “Flexible Piezoelectric-induced Pressure Sensors for Static Measurements Based on Nanowires/graphene Heterostructures", ACS Nano 11, 4507 (2017) [>350 citations]]. In addition, a highly-tunable solid-state graphene/quartz modulator has been developed [Z. F. Chen, X. Chen, L. Tao, J.B. Xu, et al., “Graphene Controlled Brewster Angle Device for Ultra-broadband Terahertz Modulation”, Nat. Commun. 9, 4909 (2018)], achieving near-perfect intensity modulation with near-perfect modulation depth and phase tunability of up to 140 degrees in a broad frequency range. This work has been highlighted by Physics World as news [https://physicsworld.com/a/varying-graphenes-conductivity-modulates-thz-wave] and the CUHK team is working with Huawei to explore collaboration and technology transfer.

Advances in energy harvesting materials and meta-structures made in this project also resulted in many highly cited papers [see, for example, H. Zhang, J.Q. Cheng, F. Lin, H.X. He, J. Mao, K.S. Wong, K.Y. Jen, C.H. Choy, “Pinhole-free and Surface-nanostructured NiOx Film by Room-temperature Solution Process for High-performance Flexible Perovskite Solar Cells with Good Stability and Reproducibility”, ACS Nano 10, 1503 (2016) [> 450 citations]; F.X. Xie, D. Zhang, H.M. Su, X.G. Ren, K.S. Wong, M. Grätzel, C.H. Choy, “Vacuum-assisted Thermal Annealing of CH3NH3PbI3 for Highly Stable and Efficient Perovskite Solar Cells”, ACS Nano 9 (1), 639 (2015) [>300 citations]; and H.N. Chen, Z.H. Wei, H.X. He, X.L. Zheng, K.S. Wong, S.H. Yang, “Solvent Engineering Boosts the Efficiency of Paintable Carbon-based Perovskite Solar Cells to beyond 14%”, Adv. Energy Mater. 6, 1502087 (2016) [> 290 citations]].

New methodologies

This AoE project promoted collaboration between theory and experiments, leading to the development of new computation and measurement methods, some with commercial value. One good example is the study of Casmir forces. Arising from quantum fluctuations, Casmir force is one of most intriguing phenomena manifesting the zero-point energy of electromagnetic fields. These quantum forces are notoriously difficult to compute and measure even for very simple geometric structures such as flat surfaces. They are even more difficult to handle, both theoretically and experimentally, for metamaterial systems (which have non-trivial microstructures). We successfully developed new methods to compute and measure these quantum forces [see, e.g., L. Tang, M. Wang, C.Y. Ng, M. Nikolic, C.T. Chan, A.W. Rodriguez, and H.B. Chan, “Measurement of Non-monotonic Casimir Forces between Silicon Nanostructures,” Nat. Photonics 11, 97 (2017); K. Ding, D. Oue, C.T. Chan, J.B. Pendry, “Casimir-induced Instabilities at Metallic Surfaces and Interfaces”, Phys. Rev. Lett. 126 (4), 046802 (2021)]

Our progress in high-precision metamaterial mechanical response measurements found applications in many areas. For example, P. Tong developed unique atomic force microscopy (AFM) techniques capable of measuring very small forces and material deformations with high precision. These techniques can be applied to many systems, from micromechanical response of nanostructured plasmonic resonant cavity and liquid interface [D.S. Guan, E. Charlaix, and P. Tong, "State and Rate Dependent Contact Line Dynamics over an Aging Soft Surface", Phys. Rev. Lett. 124, 188003 (2020)] to mechanical properties of emergent soft and living materials from living cells of different types [D.S. Guan, E. Charlaix, R.Z. Qi, and P. Tong, “Noncontact Viscoelastic Imaging of Living Cells Using a Long-Needle Atomic Force Microscope with Dual-Frequency Modulation”, Phys. Rev. Applied 8, 044010 (2017)] and protein condensates [M. Zeng, X.D. Chen, D.S. Guan, J. Xu, H. Wu, P. Tong, M.J. Zhang, “Reconstituted Postsynaptic Density as a Molecular Platform for Understanding Synapse Formation and Plasticity”, Cell 174, 1 (2018)]. The paper in Cell was selected as Best of Cell in 2018.

A very convenient method has been developed for measuring the band dispersions of metamaterial and photonic crystal slabs using thermal emission [“Angle-Resolved Thermal Emission Spectroscopy Characterization of Non-Hermitian Metacrystals”, F. Zhong, K. Ding, Y. Zhang, S.

Zhu, C.T. Chan, H. Liu, Phys. Rev. Applied 13 (1), 014071 (2020)]. A new plasmonics-based method called the ABC (Aptamer-based Bio-barcode) assay with ultra-sensitivity has also been developed for anti-cancer drug screening [H. P. Ho, S. K. Kong, "An Aptamer Bio-barcode (ABC) Assay Using SPR, RNase H, and Probes with RNA and Gold-nanorods for Anti-cancer Drug Screening", Analyst 2017 Oct 7;142(19):3579-3587. doi: 10.1039/c7an01026e].

6.2 What was the added value of the AoE funding, rather than standard project grant funding?
(For example, could this work have been achieved with other funding scheme, such as the General Research Fund or Collaborative Research Fund? If not, why?)
Wave functional materials comprise many types of advanced artificial materials including photonic/phonon/acoustic/elastic crystals, metamaterials and plasmonic structures. The length scale varies from centimeters in acoustics to nanometers in plasmonics. We would conceive such materials through advanced theoretical techniques and the wave manipulation properties would be simulated numerically. The experimental group would fabricate these materials according to the theory blueprint and the phenomena would be measured and characterized. The process would be iterated until the desired novel wave manipulation properties are achieved. We would then consider application potential enabled by the novel wave manipulation properties. The applications cover a broad scope including noise control, wave guiding, advanced imaging, biosensing and energy harvesting. Such a "material-by-design" approach encompasses theory, simulation, sample fabrication, characterization and device design; and such new materials with superior functionality can only be achieved through a well-coordinated effort among experts with different skill sets. This multidisciplinary project explored the subject matter much more broadly and deeply than would be possible with a project funded by other schemes such as the GRF or even the CRF.

6.3 If the project has not met its original objectives, why?
N/A.

6.4 (a) Please provide details of each peer-reviewed journal publication arising <u>directly</u> from this project by completing the table at **<u>Annex</u>** *(one for each publication)*.

Representative publications are listed below. The full list of publications is provided in the RGC-required format in Appendix II.

- #"Experimental observation of non-Abelian topological charges and edge states, " Q.H. Guo, T.S. Jiang, R.Y. Zhang, L. Zhang, Z.Q. Zhang, B. Yang*, S. Zhang*, C.T. Chan*, Nature 594, 195 (2021).
- #"Exceptional Nexus with A Hybrid Topological Invariant", W.Y. Tang, X. Jiang, K. Ding*, Y-X. Xiao, Z.Q. Zhang, C.T. Chan, G. Ma*, Science, 370, 1077 (2020).
- #"Classical non-Abelian braiding of acoustic modes", Z.G. Chen, R.Y. Zhang, C. T. Chan, and G. Ma*, Nat. Phys.18, 179 (2022).
- #"Topological phases in acoustic and mechanical systems," G. Ma*, M. Xiao*, C.T. Chan*, Nat. Rev. Phys. 1, 281 (2019).
- #"Towards anti-causal Green's function for three-dimensional sub-diffraction focusing," G.C. Ma*, X.Y. Fan, F.Y. Ma, J. Rosny, P. Sheng*, M. Fink*, Nat. Phys. 14, 608 (2018).
- #"Measurement of non-monotonic Casimir forces between silicon nanostructures", L. Tang, M. Wang, C.Y. Ng, M. Nikolic, C.T. Chan, A. W. Rodriguez and H. B. Chan*, Nat. Photon. 11, 97 (2017).
- #"Continuous control of nonlinearity phase for harmonic generations", G.X. Li, S.M. Chen, N. Pholchai, B. Reineke, W.H. Wong, Edwin Y.B. Pun, K.W. Cheah*, T. Zentgraf*, S. Zhang, Nat. Mater. 14, 607 (2015).
- "Geometric phase and band inversion in periodic acoustic systems", M. Xiao, G.C. Ma, Z.Y. Yang, P. Sheng, Z.Q. Zhang, C.T. Chan*, Nat. Phys. 11, 240 (2015).

- #“Flexible piezoelectric-induced pressure sensors for static measurements based on nanowires/ graphene heterostructures, Z.F. Chen, Z. Wang, X.M. Li*, Y.X. Lin, N.Q. Luo, M.Z. Long, N. Zhao, J.B. Xu*, ACS Nano 11, 4507 (2017).
- “Synthetic gauge flux and Weyl points in acoustic systems”, M. Xiao, W.J. Chen, W.Y. He, C.T. Chan*, Nat. Phys. 11, 920 (2015).
- "Acoustic metasurface with hybrid resonances", G.C. Ma, M. Yang, S.W. Xiao, Z.Y. Yang, P. Sheng, Nat. Mater. 13, 873 (2014).
- "High-responsivity graphene/silicon-heterostructure waveguide photodetectors", X.M. Wang*, ZZ. Cheng, K. Xu, H.K. Tsang*, J.B. Xu, Nat. Photonics 7, 888 (2013).
- #“Graphene and related two-dimensional materials: Structure-property relationships for electronics and optoelectronics”, X.M. Li*, L. Tao, Z.F. Chen, H. Fang, X.S. Li, X.R. Wang, J.B. Xu*, H.W. Zhu*, Appl. Phys. Rev. 4, 021306 (2017).
- “Acoustic metamaterials: from local resonances to broad horizons”, G.C. Ma*, P. Sheng*, Sci. Adv. 2:e1501595 (2016).
- #“Pinhole-free and surface-nanostructured NiOx film by room-temperature solution process for high-performance flexible perovskite solar cells with good stability and reproducibility”, H. Zhang, J.Q. Cheng, F. Lin, H.X. He, J. Mao, K.S. Wong, K.Y.Jen*, C.H. Choy*, ACS Nano 10, 1503-1511 (2016).
- #“Experimental realization of photonic topological insulator in a uniaxial metacrystal waveguide”, W.J. Chen, S.J. Jiang, X.D. Chen, B.C. Zhu, L. Zhou, J.W. Dong*, C.T. Chan, Nat. Commun. 5, 5782 (2014).
- "Surface impedance and bulk band geometric phases in one-dimensional systems", M. Xiao, Z.Q. Zhang, C.T. Chan*, Phys. Rev. X 4, 021017 (2014).
- #“Near-infrared photodetector based on MoS_2/Black phosphorus heterojunction”, L.Ye, H. Li, Z.F. Chen, J.B. Xu*, ACS Photonics 3, 692-699 (2016).
- #“Vacuum-assisted thermal annealing of CH3NH3PbI3 for highly stable and efficient perovskite solar cells”, F.X. Xie, D. Zhang, H.M. Su, X.G. Ren, K.S. Wong, M. Grätzel, C.H. Choy*, ACS Nano 9, 639 (2015).
- “Emergence, coalescence, and topological properties of multiple exceptional points and their experimental realization”, K. Ding, G.C. Ma, M. Xiao, Z.Q. Zhang, C.T. Chan*, Phys. Rev. X 6, 021007 (2016).
- “Solvent engineering boosts the efficiency of paintable carbon-based perovskite solar cells to beyond 14%”, H.N. Chen, Z.H. Wei, H.X. He, X.L. Zheng, K.S. Wong, S,H. Yang*, Adv. Energy Mater. 6, 1502087 (2016).
- “Optimal sound-absorbing structures”, M. Yang, S.Y. Chen, C. X. Fu, P. Sheng*, Mater. Horiz. 4, 673 (2017).
- "Lateral optical force on chiral particles near a surface", S.B. Wang, C.T. Chan*, Nat. Commun. 5, 3307(2014).
- “Electronic properties of MoS_2–WS_2 heterostructures synthesized with two-step lateral epitaxial strategy”, K. Chen, X. Wan, J.X. Wen, W.G. Xie, Z.W. Kang, X.L. Zeng, H.J. Chen, J.B. Xu*, ACS Nano 9 (10), 9868-9976 (2015).
- #“Effects of a molecular monolayer modification of NiO nanocrystal layer surfaces on perovskite crystallization and interface contact toward faster hole extraction and higher photovoltaic performance”, Y. Bai, H.N. Chen, S. Xiao, Q.F. Xue, T. Zhang, Z.L. Zhu, Q. Li, C. Hu, Y. Yang, Z.C. Hu, F. Huang, K.S. Wong, H.L. Yip*, S.H. Yang*, Adv. Funct. Mater. v. 26 (17), 2950-2958 (2016).
- #“On-Chip Nanophotonic Topological Rainbow”, C. Lu*, Y.Z. Sun, C. Wang, H. Zhang, W. Zhao, X. Hu*, M. Xiao, W. Ding*, Y.C. Liu, and C.T. Chan, Nat. Commun. 13, 2586 (2022).
- #“Momentum space toroidal moment in a photonic metamaterial,” B. Yang, Y.G. Bi, R.X. Zhang, R.Y. Zhang, O.B. You, Z.H. Zhu, J. Feng, H.B. Sun, C.T. Chan*, C.X. Liu*, S.

Zhang*, Nat. Commun. 12, 1784 (2021).

- # "Non-Hermitian physics for optical manipulation uncovers inherent instability of large clusters," X. Li, Y..N Liu, Z.F. Lin, J. Ng*, C.T. Chan, Nat. Commun.12, 6597 (2021).
- #"Strong geometry dependence of the Casimir force between interpenetrated rectangular gratings," M.K. Wang, L. Tang, C.Y. Ng, R. Messina, B. Guizal, J.A. Crosse, M. Antezza, C.T. Chan, H.B. Chan*, Nat. Commun. 12, 600 (2021).
- #"Shifting beams at normal incidence via controlling momentum-space geometric phases," J..J Wang, M.X. Zhao, W.Z. Liu*, F. Guan, X.H. Liu, L. Shi*, C.T. Chan, J. Zi*, Nat. Commun. 12, 6046 (2021).
- #"Delocalization of exciton and electron wavefunction in non-fullerene acceptor molecules enables efficient organic solar cells," G.C. Zhang, X.K. Chen*, J.Y. Xiao, C.Y. Chow*, M.R. Ren, G. Kupgan, X.C. Jiao, C.S. Chan, X.Y. Du, R.X. Xia, Z.M. Chen, J. Yuan, Y.Q. Zhang, S.F. Zhang, Y.D. Liu, Y.P. Zou*, H. Yan, K.S. Wong, V. Coropceanu, N. Li, J. Brabec, J.L. Bredas*, H.L. Yip*, Y. Cao, Nat. Commun. 11, 3943 (2020).
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(b) Please provide details of recognised international conference(s) in which paper(s) related to this project was/were delivered by completing the following table:
(Please attach a copy of each conference abstract)

Representative conference papers for plenary and keynote talks are shown below. The full list of invited talks is provided in Appendix III.

Month/Year/ Place	Title	Conference name	Submitted to the RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of the RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Sep/ 2021/ Tbilisi	Optical Pulling using Unidirectional Surface Waves [keynote]	METANANO 2021	2021	Yes	Yes	No
Nov/2019, Xian China	Some electromagnetic ‘twisting’ structures with unusual optical properties [Plenary]	首届全国超材料大会	2020	No	Yes	No
Dec/2019/ Korea	Topological Characters of Simple Photonic Crystals [plenary]	4th POSTECH Nanophotonics Tutorial Workshop	2020	No	Yes	No
Jan /2019/ Seefeld, Austria	Metamaterials with twisting structures [plenary]	7th International Topical Meeting on Nanophotonics and Metamaterials	2019	No	Yes	No
June/2019/ Hong Kong	Topological photonic crystals [plenary]	The 9th International Multidisciplinary Conference on Optofluidics	2019	No	Yes	No
July/2019/ Guangzhou	An integration strategy for acoustic metamaterials to achieve absorption by design [plenary]	Great Bay Area Symposium for Wave Functional Materials	2019	No	Yes	No
June/2019/ Hong Kong	An integration strategy for acoustic metamaterials to achieve absorption by design [keynote]	9th International Multidiscipline Conference on Optofluidics	2019	No	Yes	No
Dec/2017/ Honolulu	Optimal sound-absorbing structures [plenary]	2017 International Congress on Ultrasonics	2018	No	Yes	Yes

July/ 2018/ London	Acoustic metamaterials with ultra-broadband absorption and minimum thicknesses [plenary]	European Workshop on Acoustic & Mechanical Metamaterials	2018	No	Yes	No
July/ 2018/ Krakow, Poland	Optimal sound absorbing structures [plenary]	11th International Conference on Electrical, Transport and Optical Properties of Inhomogeneous Media (ETOPIM11)	2018	No	Yes	No
October /2017/Nanjing	Twisting-induced synthetic gauge potential [keynote]	The Nanjing Forum 2017: Cutting-edge Science and Future Technology	2018	No	Yes	Yes
Nov/ 2017/Singapore	Metamaterials with a ‘twist’ [keynote]	PIERS 2017	2018	No	Yes	Yes
Dec/ 2017/ Le Mans, France	Optimal sound-absorbing structures [keynote]	5th Symposium on the Acoustics of Poro-Elastic Materials	2018	No	Yes	No
May/ 2018/Hangzhou	Forces between neutral nano plasmonic objects [keynote]	International Symposium On Plasmonics and Nanophotonics 2018	2018	No	Yes	Yes
Aug/2018/ Toyama, Japan	Curvature-induced forces between nano-corrugated plasmonic surfaces [keynote]	PIERS 2018	2018	No	Yes	No
Jun/2017/ Changsha	"Optimal sound-absorbing structures" [Plenary]	4th International Conference on Phononic Crystals/Metamaterials, Phonon ransport/Coupling and Topological Phononics	2017	No	Yes	No
Jan/ 2017/ Macau	“Computational approach to wave functional materials” [Plenary]	ICCP10: 10th International Conference on Computational Physics	2017	No	Yes	No
Nov/2017/ Singapore	“Metamaterials with a ‘twist” [Keynote]	PIERS 2017	2017	No	Yes	No
Aug/2017/ San Diego	“Index ellipsoids at arbitrary k-points ” [Keynote]	SPIE Active Photonic Platforms IX	2017	No	Yes	No
July/2017/ Incheon, Korea	“Pseudo-spins and their consequences in classical waves” [Keynote]	META'17	2017	No	Yes	No
Nov/2016/ Shenzhen	"Optimal sound-absorbing structures" [Keynote]	Forum of Advanced manufacturing and Micro-Nanocomposite Multifunctional Materials	2017	No	Yes	No
October /2015/ Qingdao	“Investigation of graphene and graphene like materials” [Plenary]	2015 International Graphene Innovation Conference	2017	No	Yes	No
Sept/2016/ Crete	"Topological principles and exceptional point Physics realized using simple meta-crystals" [Plenary]	The 10th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics [Metamaterials'2016]	2016	No	Yes	No

May/2016/ Xian	"Using acoustic systems to illustrate topological and parity-time symmetry concepts" [Plenary]	The 3rd International Conference on Phononics and Thermal Energy Science [PTES2016]	2016	No	Yes	No
June/2016/ Edinburgh	“Absorption of sound using subwavelength structures” [Plenary]	Workshop on Metamaterials beyond Photonics	2016	No	Yes	No
Aug/2016/ Shanghai,	"Zero-refractive index and pseudo-spin physics in photonic systems" [Keynote]	PIERS 2016	2016	No	Yes	Yes
Dec/2015/ Dongguan	“Using novel artificial materials to manipulate light" [Keynote]	2015 Workshop on the Frontier of Novel functional Material and High-Tech Applications	2016	No	Yes	No
Oct/ 2015/ Hangzhou	"Conical dispersion and Pseudo-Spin Physics", [Keynote]	AOM 2015: The 5th Conference on Advances in Optoelectronics and Micro/Nano-optics	2016	No	Yes	No
Dec/ 2015/Singapore	“Hybrid resonance and the realization of point acoustic sink” [Keynote]	Western Pacific Acoustics Conference	2016	No	Yes	No
Nov/2015/ Houston, USA	“Hybrid resonance and the realization of point acoustic sink” [Keynote]	ASME 2015 International Mechanical Engineering Congress and Exposition	2016	No	Yes	No
Aug/2015/ Shenzhen, China	"Using metamaterials to manipulate light” [Plenary]	IEEE OGC 2015: The Optoelectronics Global Conference	2015	No	Yes	No
Jun/2015 /Wuhan, China	“Consequences of Dirac-like cone dispersions in optics” [Plenary]	POEM 2015 [International Photonics and OptoElectronics Meetings]	2015	No	Yes	Yes
July/2015/ Prague, Czech Republic	“Nonlocal effective medium theory and its relation with Zak phase in two-dimensional photonic crystals” [Keynote]	PIERS 2015	2015	No	Yes	No
Dec/2014/ Hong Kong	"Using light to move things around" [Plenary]	IWCSE 2014 [International Workshop on Computational Science and Engineering]	2015	No	Yes	No
May/2014/ Shanghai	"Zak phase and gap inversion in periodic acoustic systems" [Plenary]	PTES 2014	2014	No	Yes	No
Nov/2014 /Suzhou	"Robust interface states derived by Dirac cone dispersions” [Plenary]	International Workshop on Wave Functional Materials	2014	No	Yes	No
Nov/2013 /Suzhou	"Membrane type acoustic metamaterials" [Plenary]	the International Workshop on Wave Functional Materials	2014	No	Yes	No
Jun/2014/ Hong Kong	"Hybrid resonance and the realization of point acoustic sink" [Plenary]	17th Annual Conference of the Physical Society of Hong Kong	2014	No	Yes	No
Aug/2014 /Guangzhou	"Acoustic metasurface with hybrid resonances" [Keynote]	PIERS 2014	2014	No	Yes	No

(c) UGC/RGC funding should have been acknowledged in all publication(s)/conference papers listed in (a) and (b) above. If no acknowledgement has been made in any of the publications/papers, please indicate and provide explanations.
N/A

6.5 To what extent this project has strengthened inter-institutional collaborations and other partnerships?

In this AoE project, we adopted a "material-by-design" approach involving theory, simulation, fabrication and characterization, which naturally requires collaboration between theory and experimental groups and the sharing of facilities and expertise among different institutions. The PC's group provided "on-demand" theory/simulation support to all experimental teams. We jointly supervised students and postdoctoral fellows. For example, Fung (PolyU) and Chan (HKUST) jointly hosted and supervised one visiting scholar working on various projects, including the dynamical effects of metamaterials. Ng (HKBU) and Chan (HKUST) jointly supervised one postdoctoral fellow working on optical forces and light manipulation of matter. Fung (PolyU) collaborated with the HKBU team on the modelling of organic plasmonic structures. The CUHK plasmonics group and Chan's group (HKUST) jointly developed a new simulation method. Pun (CityU) assisted various groups with nano-fabrication using CityU facility, including the CUHK group with E-beam fabrication of plasmonic structures, Tam (HKUST) with photonic crystal fabrication and Cheah (HKBU) with fabrication of various nano-devices. HB Chan (HKUST) assisted various groups with nano-characterization using facilities at HKUST. Wong (HKUST) and Xu (CUHK) collaborated on nano-structure fabrication for enhancement of solar energy harvesting. HKUST, HKUB and PolyU also jointly hosted visitors working on various topics. The project has thus strengthened inter-institutional partnerships immensely.

6.6 Research students trained (registration/awards):

PhD students trained in this project are listed in the table below. See Appendix IV for a list of MPhil students and other students who also received training through this project.

Name	Degree Registered for	Date of Registration	Date of Thesis Submission / Graduation
Burkhartsmeyer Jeffery	PhD in Physics	Sept 2014	Current student
Chang Mingli	PhD in Physics	Sept 2014	Aug 2021
Chen Jie-Jie	PhD in Electronic Engineering	Sept 2011	July 2016
Chen Qihong	PhD in Nano Science and Technology	Sept 2012	Jan 2017
Chen Xuee	PhD in Nano Science and Technology	Sept 2018	Current student
Chen Yu	PhD in Physics	Sept 2021	Current student
Chen Zefeng	PhD in Electronic Engineering	Sept 2013	June 2017
Cheng Man Kit	PhD in Physics	Sept 2016	Current student
Ching Suet Ying	PhD in Physics	Jan 2011	Nov 2015
Choi Tat Shing	PhD in Physics	Sept 2014	Nov 2018
Cong Hengji	PhD in Electronic Engineering	Aug 2015	July 2019
Cui Xiaohan	PhD in Physics	Sept 2014	Aug 2019
Dai Cheng	PhD in Physics	Sept 2018	Current student
Deng Xiaohui	PhD in Physics	Sept 2015	July 2021

Dong Xiaoshi	PhD in Physics	Sept 2014	May 2019
Dong Zhen	PhD in Physics	Sept 2015	Current student
Fatemeh Hosseini Alast	PhD in Physics	Jan 2013	Nov 2017
Gao Nan	PhD in Physics	Sept 2019	Current student
Gao Ziang	PhD in Physics	Sept 2015	May 2020
Gu Ruinan	PhD in Physics	Sept 2016	Current student
Guan Dongshi	PhD in Physics	Sept 2010	Mar 2016
Han Chengxiao	PhD in Physics	Sept 2018	Current student
Han Chunrui	PhD in Nano Science & Technology	Sept 2010	Jan 2014
He Meng Yuen	PhD in Physics	Sept 2012	Nov 2020
He Jun	PhD in Physics	Sept 2012	Aug 2017
He Xiangxu	PhD in Physics	Sept 2019	Current student
He Yuman	PhD in Physics	Sept 2020	Current student
He Wenyu	PhD in Physics	Sept 2015	Nov 2018
Ho Sui Lun	PhD in Physics	Sept 2019	Current student
Hou Yuxiao	PhD in Physics	Sept 2019	Current student
Hu Chuandeng	PhD in Physics	Sept 2016	Sept 2020
Hu Mengli	PhD in Physics	Sept 2018	Current student
Huang Linhai	PhD in Physics	Sept 2015	Jan 2021
Huang Yongjie	PhD in Physics	Sept 2021	Current student
Jiang Tianshu	PhD in Physics	Jan 2017	Dec 2020
Kowk Ho Chin	PhD in Electronic Engineering	Sept 2011	Dec 2019
Kuang Guowen	PhD in Physics	Sept 2013	Aug 2017
Lam Ka Hei	PhD in Mechanical Engineering	Jan 2016	Current student
Lam Man Yu	PhD in Nano Science and Technology	Sept 2021	Current student
Leung Ho Ming	PhD in Physics	Feb 2012	Jan 2017
Li Bo	PhD in Physics	Sept 2012	Jan 2018
Li Hao	PhD in Electronic Engineering	Sept 2013	Feb 2020
Li Wei	PhD in Physics	Sept 2014	Nov 2019
Li Xiao	PhD in Physics	Sept 2014	Aug 2017
Liang Jing	PhD in Physics	Sept 2015	Aug 2019
Liao Maijia	PhD in Physics	Sept 2011	Sept 2016
Liao Zhitao	PhD in Physics	Sept 2019	Current student
Lin Min	PhD in Physics	Sept 2013	Jan 2019
Liu Shiye, Dora	PhD in Biochemistry	Sept 2017	Current student
Loo Fong Chuen	PhD in Biochemistry	Sept 2011	Nov 2015
Lu Yao	PhD in Physics	Sept 2011	Aug 2017
Luo Xiao	PhD in Physics	Sept 2019	Current student
Lyu Guoqing	PhD in Physics	Sept 2013	Aug 2017
Ma Chao	PhD in Physics	Sept 2016	Aug 2020
Mai Jianming	PhD in Physics	Sept 2020	Current student
Mak Ho Yiu	PhD in Physics	Sept 2018	Current student
Mao Ningbin	PhD in Physics	Sept 2021	Current student
Meng Chong	PhD in physics	Sept 2013	Aug 2016
Ngai Tze Ue	PhD in Physics	Sept 2019	Current student
Pan Jie	PhD in Physics	Sept 2012	Aug 2016

Qu Qing	PhD in Nano Science and Technology	Sept 2017	May 2021
Qu Sichao	PhD in Physics	Sept 2019	Current student
Shen Fuhuan, Terry	PhD in Electronic Engineering	Sept 2018	Current student
Shen Junying	PhD in Physics	Sept 2013	Aug 2017
Su Yun	PhD in Physics	Sept 2011	July 2017
Tang Minghui	PhD in Electronic Engineering	Aug 2014	June 2018
Tang Suet To	PhD in Physics	Sept 2015	Nov 2020
Tang Xingwei	PhD Nano Science & Technology	Sept 2018	Current student
Tao Li	PhD in Electronic Engineering	Sept 2014	Oct 2018
Tong Rui	PhD in Nano Science and Technology	Sept 2016	Aug 2019
Tse Tin Yau	PhD in Physics	Sept 2016	Current student
Wang Cong	PhD in Nano Science & Technology	Sept 2012	Aug 2015
Wang He	PhD in Physics	Oct 2013	Aug 2017
Wang Li	PhD in Physics	Sept 2014	May 2018
Wang Mingkang	PhD in Physics	Sept 2013	Dec 2018
Wang Yin	PhD in Physics	Sept 2011	Dec 2017
Wei Yuanyaun	PhD in Biomedical Engineering	Aug 2018	Current student
Wen Xinhua	PhD in Physics	Sept 2018	Current student
Wen Yan	PhD in Physics	Sept 2018	Current student
Wong Sung Ching	PhD in Physics	Sept 2012	Aug 2017
Wong Yu Ching	PhD in Nano Science and Technology	Sept 2020	Current student
Wu Daihui	PhD in Nano Science and Technology	Sept 2018	Current student
Wu Pak Hong	PhD in Applied Physics	June 2014	June 2019
Wu Xiaoxiao	PhD in Physics	Sept 2014	Aug 2018
Xia Zengzilu	PhD Nano Science & Technology	Sept 2014	Jan 2018
Xiao Meng	PhD in Physics	Sept 2010	Aug 2014
Xiao Songwen	PhD in Physics	Sept 2012	Aug 2016
Xiao Yixin	PhD in Physics	Sept 2011	Aug 2017
Xing Zengshan	PhD in Physics	Sept 2019	Current student
Xu Fang	PhD in Electronic Engineering	Sept 2013	Sept 2018
Xu Hanqi	PhD in Nano Science and Technology	Sept 2018	Current student
Xu Wei	PhD in Nano Science and Technology	Sept 2014	June 2020
Yan Caishan	PhD in Physics	Sept 2016	Current student
Yan Yingming	PhD in Physics	Sept 2017	Current student
Ye Ziran	PhD in Physics	Sept 2013	Jan 2016
Yuan Fanqi	PhD in Physics	Sept 2014	Aug 2017

Yung Tsz Kit	PhD in Physics	Sept 2016	Nov 2019
Zeng Xiping	PhD in Nano Science and Technology	Sept 2012	Aug 2015
Zhang Bing	PhD in Physics	Sept 2012	Aug 2016
Zhang Boqi	PhD in Physics	Sept 2018	Current student
Zhang Lu	PhD in Physics	Sept 2014	Aug 2016
Zhang Qi	PhD in Physics	Sept 2016	Current student
Zhang Ran	PhD in Physics	Sept 2014	Aug 2019
Zhang Wanyi	PhD in Biomedical Engineering	August 2020	Current student
Zhang Xiaonan	PhD in Physics	Sept 2015	Dec 2020
Zhang Yilin	PhD in Physics	Sept 2010	Aug 2015
Zhou Bingpu	PhD in Nano Science & Technology	Sept. 2012	Jan 2015
Zhou Yaoqiang	PhD in Electronic Engineering	Sept 2019	Current student
Zhu Shaodi	PhD in Biomedical Engineering	Aug 2021	Current student

6.7 Specific products (e.g. software or netware, instruments or equipment developed):

As a result of our breakthrough in resonance-based acoustic metamaterials, students from Ping Sheng's group (Dr. Shuyu Chen and Dr. Min Yang) have founded a start-up company—Acoustic Metamaterials Group (AMG), which ranked no. 1 in annual product shipment of acoustic metamaterials among the six peer companies worldwide in 2020-21. As an example of its recent success, AMG has partnered with KEF, a top UK hi-fi speaker company, to develop a new line of speakers with metamaterial absorption technology. These speakers (LS50 Meta) won product of the year award in 2021 (https://hk.kef.com/pages/ls50-meta?gclid=Cj0KCQjwhsmaBhCvARIsAIbEbH4P5UbB6r2nioAcxGs8kVLK5Bqeveq9JRr0jfGlXNfn2M3Ddmzn67IaAr_8EALw_wcB); https://www.whathifi.com/news/what-hi-fi-awards-26-product-of-the-year-winners-announced-for-2021). More product information can be found at the company website: http://www.metacoust.com.

K.S. Wong and his students co-founded a start-up company, Centauri Optics, to commercialize a low-cost and high-performance microscope. The microscope utilizes fluorescent imaging for point-of-care, rapid diagnosis. Product information can be found at https://www.centaurioptics.com/.

W.J. Wen's students started a company that markets and sells metamaterial-based products, including resonators, antennae and characterization hardware/software such as computer-controlled scanners that can measure surface and bulk waves of metamaterials. Product information can be found at http://fantwave.com/sy.

K.W. Cheah founded Cathay Photonics Limited (https://cathayphotonics.com), which developed an innovative approach to fabricate sapphire thin films on a transparent substrate. The "Scratch Proof Thin Film on Glass" technology has won multiple awards, including Gold medal and Grand Prix (Champion) International Invention Award at the 44th International Exhibition of Inventions Geneva; Special Award, 44th International Exhibition of Inventions of Geneva; Excellence Award (the second prize) in the Guangdong-Hong Kong-Macao Greater Bay Area High-Value Patent Portfolio Contest 2021; and Gold Medal with the Congratulations of Jury, International Exhibition of Inventions of Geneva 2021. This technology was featured in the TV program "Living with the Benefits of Research". (27/12/2021) [TV program link:

https://www.youtube.com/watch?v=fbEqVwQFpLw]

6.8 Other education activities and/or training programmes developed
Every research team in this collaboration supervised and trained postdoctoral fellows and graduate students actively (see Appendix IV). The team members also disseminated knowledge to students enthusiastically through various channels. For example, the PI taught summer schools and tutorials on-line using results from this AoE. He gave an on-line tutorial on metamaterials and photonics to graduate students in mainland China in 2021. Organized jointly by Nanjing University and Soochow University, the tutorial was also attended by a large number of students from more than 20 universities outside of Nanjing, China, and Taipei, Taiwan. He also taught via Zoom a summer school on topological bosonics and electronics using results from this AoE. The summer school was attended mostly by European students. Members of the AoE team gave talks in secondary schools using light and sound as examples to promote STEM. Members also gave public lectures at venues including the Hong Kong Science Museum, Hong Kong Public Libraries, and the Hong Kong Convention and Exhibition Centre to enhance public awareness of the use of modern wave manipulation technology in our daily life. The PI has always been active in promoting science (for example, by giving talks at four high schools in 2022).

6.9 Please highlight any deliverables indicated in the project implementation timetable endorsed by the UGC/RGC which have not been covered or achieved as per sections 6.1 to 6.8 above, and explain/ elaborate.
N/A

Project Management

6.10 Please elaborate how the PC has played his/her role in coordinating and managing the project.
The PC organized regular meetings among the project team members, leading to the exchange of ideas that are crucial to the collaboration. The minutes of the meetings had been attached to each of the annual reports. The PC chaired the executive committee meetings, during which the progress of the project was reviewed and the distribution of funding was determined collectively. The PC also met with individual subgroups (via Zoom during the pandemic) from time to time to monitor the progress. The PC's team provided theoretical and numerical simulation support to every experimental group in the AoE team. The PC, in conjunction with the HKUST Jockey Club Institute for Advanced Study at HKUST, organized visitor programs on metamaterials where international experts and distinguished speakers from around the world were invited to Hong Kong to interact and exchange ideas with the AoE team. He organized symposiums/workshops (typically two a year) to promote interaction of our team with international experts and to increase our team's visibility. He founded the "Greater Bay Area Symposium for Wave Functional Materials" in 2018, which has become an annual event (held on-line during the pandemic). He also organized symposiums for junior members (postdocs) from different research groups to exchange ideas and information and promote collaboration._

7. Awards and Recognition

7.1 Have any research grants been awarded that are directly attributable to the results obtained from this project?

Yes. Please see Section 9.2.

7.2 Have any project team members participated as invited speakers in or organisers of international conferences as a result of this project?

Yes. Team members have been invited to present plenary, keynote, and invited talks in international conferences. For plenary and keynote talks, please see Section 6.4(b). For a list of invited talks, please see Appendix III. Members of the team have also participated in the organization of many meetings held internationally.

7.3 Have any project team members taken leadership positions in editorial boards, scientific and professional organisations?

K.W. Cheah: Editorial board member of Journal of Modern Optics (JMO) and Photonics
Jack Ng: Editorial board member of Scientific Reports
J.B. Xu: Associate editor of Science Bulletin; editorial board member of ACS Nano; deputy chairman of Hong Kong Materials Research Society
K.H. Fung: Editor of Open Physics
C.T. Chan: Associate editor of ACS photonics; editorial board member of Physical Review B, Europhysics Letters and Journal of Applied Physics;
Aaron Ho: Editor of "Microfluidic Biosensors"; chairman of Hong Kong Optical Engineering Society
P. Tong: Editorial board member of Chinese Physics B and Acta Physica Sinica.
P. Sheng: Executive editorial board member of Solid State Communications; divisional associate editor of Physical Review Letters; editorial board member of the New Journal of Physics, the Proceedings of Royal Society A, the SIAM Journal of Mathematics: Multiscale Modeling, Analysis, and Simulation; advisory board member of the Research Center for Applied Sciences, Academia Sinica; national board member of Kavli Institute of Theoretical Physics, China.

7.4 Any documentary proof of the application of technologies arising directly from this project?
N/A

7.5 Other awards and recognitions as a result of this project (please specify):

C.T. Chan: Elected the inaugural Fellow of the Physical Society of Hong Kong (2018); elected a member of the Hong Kong Academy of Sciences (2021); co-recipient of Brillouin Medal with P. Sheng (2013).
K.W. Cheah: IAAM Scientist of the Year Award 2020, the International Association of Advanced Materials (IAAM).
P. Sheng: The 2018 winner of the Landauer Medal from the international ETOPIM Society; elected as Member of the Hong Kong Academy of Sciences (2019); elected as Honorary Member and Fellow of the Physical Society of Hong Kong in 2020; co-recipient of Brillouin Medal with C.T. Chan (2013).
Aaron Ho: Elected Fellow of SPIE (2015).
J.B. Xu: Elected IEEE Fellow (2018).

8. Impacts

8.1 What are the current and expected impacts of the project in terms of its contribution to the local and regional economic and societal well-being (e.g. patent, technology transfer, collaboration with external organisations, etc.)?

Patents:

Lead Inventor	Title	Patent number	
Kok	Fabrication of highly flexible near-infrared	US US9610754B	Granted

Wai Cheah	metamaterials	2	2017-04-04
Kok Wai Cheah	Sapphire thin film coated substrate	US9695501B2	Granted 2017-07-04
Kok Wai Cheah	Sapphire thin film coated flexible substrate	US10227689B2	Granted 2019-03-12
Kok Wai Cheah	Nano bi-material electromagnetic spectrum shifter	EP3458625A4	Published 2020-07-29
Kok Wai Cheah	Tunable amplified spontaneous emission (ase) laser	US20170163011 A1	Published 2017-06-08
Kok Wai Cheah	Tunable laser materials comprising solid-state blended polymers	US20210203122 A1	Published 2021-07-01
Kok Wai Cheah	Metal substrate coatings	WO2022156820 A1	Published 2022-07-28
Ho Pui Ho Siu Kai Kong	Optical sensing apparatus and a method for detecting characteristics of a sample	US 9,322,778 B2	Published 2016-04-26
Ho Pui Ho Siu Kai Kong	Centrifugal microfluidic control systems and method for configuring the same	US10220388B2	Granted 2019-03-05
Ho Pui Ho Siu Kai Kong	用于检测样本特性的光学传感装置和方法	ZL201510196717 . 2	Published 2017-09-19
Siu Kai Kong	Methods and devices for rapid detection of target genetic material	US20210395819 A1	Published 2021-12-23
Ping Sheng	Low frequency acoustic absorption and soft boundary effect with frequency-discretized active panels	US10991358B2	Granted 2021-04-27
Ping Sheng	Sound attenuating structures	US9466283B2	Granted 2016-10-11
Ping Sheng	Vibration damped sound shield	US10482865B2	Granted 2019-11-19
Ping Sheng	Active control of membrane-type acoustic metamaterial	US9659557B2	Granted 2017-05-23
Ping Sheng	Extraordinary acoustic absorption induced by hybrid resonance and electrical energy generation from sound by hybrid resonant metasurface	US9711129B2	Granted 2017-07-18
Ping Sheng	Binary spatial sound modulator for adaptive wavefield shaping	WO2019122942 A1	Published 2019-06-27
Ping Sheng	Compact low-frequency wave absorption device	WO2020038409 A1	Published 2020-02-27

Technology transfer: A few start-up companies have been founded to transform the ideas arising from this project into useful products. Please see Section 6.7.

Societal impact: Among all the start-ups founded by various teams on this project, the company (Acoustic Metamaterials Group) founded by Ping Sheng's team has the largest operation in terms of sales volume. In addition to applying cutting-edge knowledge of acoustic metamaterials to high-end products (e.g. hi-fi speakers), the company is also developing a technology that uses recycled plastic and plastic waste material to build sound-absorbing structures. They have plans to build a production line in Hong Kong. If successful, they can transform plastic waste in Hong Kong into useful products.

Collaborations with external organizations: Team members actively collaborated with researchers in other parts of China (including, for example, Peking, Tsinghua, BIT, Nanjing, Fudan, Ningbo, Soochow, Sun Yat-sen, SCUT, Wuhan, Chongqing), USA (Berkeley, MIT, Cornell, Princeton, U of Delaware, U of Washington, U of Florida, ORNL, NC State), Europe (Imperial, Birmingham, UCL, Bath, Leeds, Le Mans, Lausanne, Paderborn, CNR-Italy, València) and Singapore (NTU, NUS, A*STAR).

8.2 Others (please specify):

N/A

9. Sustainability of the Project

9.1 Whether there are new ideas evolved directly from this project?

Yes, there are. Examples are:
Breaking causality: To achieve broadband absorption functionality, passive acoustic metamaterials should be achieved through a design strategy that is integrated with the causality principle, which sets a minimum thickness limit on the absorbing structure. The same rule applies to electromagnetic waves. In order to break the lower bound, we need to employ active metamaterials, which means a source and a sink are needed. We expect the next breakthrough in meta-acoustics will come from breaking the causality bound by going into non-Hermitian acoustics. We are working along these lines now.
Connecting different fields of research: Hidden relationships exist between seemingly unrelated phenomena that, when unravelled, can lead to important breakthroughs. For example, we discovered a hidden relationship between non-Hermitian topological physics and singular optics (the latter concerned with topics such as polarization singularities, caustics, and bound states in the continuum). Traditionally studied as separate research topics, we found that these phenomena can be described using the same theoretical framework, and hence many known results in one field can inspire new research directions in another field. Another interesting discovery is concerned with optical clusters. We found that the stability condition of particles and clusters stabilized by optical forces is closely related to exceptional point physics and thus the known results of exceptional point physics may lead to new ideas and new discoveries in optical tweezer research.
Bringing non-Abelian physics ideas to photonic and phononic systems: The classification of topological states is the cornerstone of topological physics. Going beyond the usual classification of single-gap topological phases using Abelian topological charges, multi-gap insulators can be topologically classified by non-Abelian quaternion groups with noncommutative topological charges. This non-Abelian approach to multi-gap topological phases is particularly useful for bosonic and classical waves, as the frequencies available in these systems can span all bandgaps.
Synergism of material and structural properties: The conventional paradigm of metamaterial research focuses on using microstructures to induce functionality, assuming that the intrinsic material/electronic properties are independent of structure. With advances in nanomaterial research, the intrinsic material/electronic properties of the constituent material can also be manipulated through structural modification. The combined control of electronic and optical properties through the nano/microstructure can yield very potent opto-photonic devices.

9.2 Whether there are new projects evolved directly from this project?

Yes, there are.

Title	Funding source	Start/end dates	HK$
Meta-optics, Meta-acoustics and Meta-devices	AoE AoE/P-502/20	01-May-2021 30-Apr-2029	65,552,000

Joint Laboratory for Wave Functional Materials Research	Croucher Foundation	01-Jan-2021 31-Dec-2023	3,000,000
Non-Hermitian Systems in Optics and Acoustics	CRF C6013-18G	01-Mar-2019 28-Feb-2022	7,279,742
Broadband Absorbers for Microwaves and Ultra-low Frequency Mechanical Waves	RIF R6015-18	01/04/2019 31/03/2024	9,727,950

9.3 Whether there are new collaborations developed directly from this project?

Yes. Please see Section 8.

9.4 Please give details on how much money and from which sources has been obtained/requested for the specific purpose of continuing the work started under this project.

Please see Section 9.2.

10.Statistics on Research Outputs

(Please ensure the statistics in this section are consistent with the information presented in other sections of this report.)

	Peer-reviewed journal publications	Conference papers	Scholarly, books, monographs and chapters	Patents awarded	Other research outputs (please specify) Type	No.
No. of outputs arising directly from this research project	449	212	3	18	No	No

11. Public Access of Completion Report

(PCs of projects funded in 2010/11 academic year or onwards are required to release the completion reports to the public through the RGC website. Completion reports containing information such as abstracts in non-technical terms, objectives, research output including the list of conference papers / publications / journals and research findings and contact information of PCs should be open to public access.)

Please specify the information, if any, that cannot be provided for public access and give the reasons.

Information that cannot be provided for public access	Reasons
No	Not applicable

<u>12. The Layman's Summary</u>

(describe in layman's language the abstracts and research impact of the project.)

The diverse applications of electromagnetic and acoustic waves form the very pillars of modern civilization. About two decades ago, a revolution began in this classic field, after theory and experiments demonstrated the feasibility of realizing man-made materials with wave manipulation functionalities beyond the defined limits of those found in nature. These "wave functional materials" include photonic and phononic crystals, metamaterials and plasmonic structures. The purpose of this AoE project, based on the existing strengths of Hong Kong researchers and their pioneering efforts in this rapidly evolving area, was to lift our collective knowledge and capability one notch higher, with an eye towards potential applications that can support and define the next generation of wave-related devices.

The simplest example of a wave functional material is the lens in a microscope or telescope. Ordinary lenses are made of a single material, glass, with crafted surfaces. By employing multi-component composites in conjunction with advances in theory and fabrication technology, new degrees of freedom in controlling waves have now become available. The new materials thus fabricated can be optimized for a specific functionality. If the constituent structures and the lattice period are smaller than the wavelength, the material is called a "metamaterial;" if they are close to the wavelength, the material is called a "photonic crystal;" and if the units are made of nano-scale metallic structures, the material is called a "plasmonic structure."

After eight years of concerted effort and collaboration, the team members are now at the forefront of this exciting scientific development. We introduced fundamentally new concepts and some of the developments lay the foundation for future technologies. Here we illustrate a few of our accomplishments.

Sound absorption is important for room acoustics and the remediation of noise can improve our quality of life. The sound absorption structures using conventional porous and fibrous materials are either bulky or structurally weak or both. the team designed new acoustic metamaterials and realized the "best" absorber performance as allowed by the laws of nature (the causal principle of the acoustic response). The metamaterial absorbing structures are ultra-thin and structurally robust. This breakthrough drew world-wide attention from academia and industry and the associated acoustic metamaterials were successfully commercialized.

Electromagnetic waves are the main carrier for communications and the transmission of information. Waves of all lengths are used, from radio waves, microwaves, infrared radiation to light. But all forms of wave transport are compromised by scattering due to imperfections in the wave-carrying medium. Can artificial materials be designed whose signal transport functionality is immune to imperfections or disorder? The answer is affirmative. Using modern theories of topological physics, we demonstrated that electromagnetic and acoustic wave transport will not be interrupted by imperfections or disorder if we employ topological photonic crystals and metamaterials, which carry surface modes that move in a single direction and the propagation cannot be stopped by mild or even moderate perturbations.

Another advance we have made is the combination of electronic and optical properties to enhance wave manipulation effects. Let us again use lenses as an example. Conventional lenses are crafted glass components with simple curved surfaces. Photonic crystals can be regarded as a very advanced lens in which a great many micro crafted surfaces exist within a very small volume of the lens; and the complexity of the structure gives us extra functionality. If the microstructure is so small (down to the nano-scale) such that the electronic structure of the material is also changed due to the nano-morphology, then we have an additional degree of freedom to modulate/control the wave properties. This can lead to more potent devices such as advanced sensors and energy-harvesting devices, which are useful in our daily lives.