RGC Ref.:M-HKUST601/12
(please insert ref. above)

The Research Grants Council of Hong Kong
SRFDP & RGC ERG Joint Research Scheme
Completion Report

(Please attach a copy of the completion report submitted to the Ministry of Education by the Mainland researcher)

Part A: The Project and Investigator(s)

1. Project Title

Enhancement of polarizabilities of small particles through particle-substrate resonances

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Che Ting Chan	Hui Liu
Post	Chair Professor	Professor
Unit / Department / Institution	PHYS/HKUST	National Laboratory of Solid State Microstructures and School of Physics, Nanjing University
Contact Information	e-mail: phchan@ust.hk	e-mail: liuhui@nju.edu.cn
Co-investigator(s) *(with title and Institution)*	not applicable	not applicable
PhD student(s) (with period of involvement)	Name: Meng Xiao Institution: HKUST Period from Mar, 2013 to Aug, 2014 (continued involvement as postdoc until Aug 2015)	Name: Qiang Wang, Chong Sheng, Fang Zhong Institution: Nanjing Period from Mar, 2013 to Feb, 2016
	Name: Shubo Wang Institution: HKUST Period from Mar 1, 2013 to Aug, 2013 (continued involvement as postdoc until Feb 2016)	

	Name: Xiaohan CUI Institution: HKUST Period from Aug, 2014 to Feb, 2016	

Note: The Hong Kong project team must involve at least one research postgraduate student pursuing a Doctor of Philosophy degree at the UGC-funded university (PhD student) at any time throughout the project period.

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted*)
Project Start date	Mar 1, 2013		
Project Completion date	Feb 29, 2016		
Duration *(in month)*	36		
Deadline for Submission of Completion Report	Feb 28, 2017		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. Investigate the necessary conditions for the formation of reflection- and resonance-enhanced polarizability when a particle is placed near a metamaterial substrate. We will start with the simple case of a small particle placed in front of a homogeneous slab characterized by frequency-dependent permittivity and permeability and move on to more complex configurations.

2. Explore the physical consequences of polarizability enhancements, enhanced particle-field interaction effects, and related effects.

5.2 Revised Objectives

Date of approval from the RGC: not applicable

Reasons for the change: not applicable

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2.
3. ....

6. Research Outcome

Major findings and research outcome
(maximum 1 page; please make reference to Part C where necessary)

Results concerning the first objective is summarized in a paper published in [Sci Rep. 5: 8189 (2015)]. We found that if the size of an object is very small compared with the wavelength of light, it does not scatter light efficiently. However, we show using analytic theory as well as full wave numerical calculation that the effective polarizability of a small cylinder can be greatly enhanced by coupling it with a metamaterial slab. This kind of enhancement is not due to the individual resonance effect of the substrate, nor that of the small particle, but is enabled by a collective resonant mode that exists between the particle and the substrate. We show that this type of particle-slab resonance which makes a small object much brighter is actually closely related to the reverse effect known in the literature as "anomalous resonance" that can make an object invisible.

For the second objective, we found that the enhanced particle-substrate resonances can lead to strong and novel optical forces. Results are published in [Nat. Commun. 5, 3307 (2014) and Opt. Exp., 24, 2235 (2016)]. We demonstrate, using full-wave simulations, that an anomalous lateral force can be induced in a direction perpendicular to that of the incident photon momentum if a chiral particle is placed above a substrate that does not break any left–right symmetry. Analytical theory shows that the lateral force emerges from the coupling between structural chirality (the handedness of the chiral particle) and the light reflected from the substrate surface. Such coupling induces a sideway force that pushes chiral particles with opposite handedness in opposite directions. We theoretically and

numerically demonstrate a mechanism that can significantly enhance the optical force acting on a small particle through a special type of resonant particle-substrate coupling. The resonance arises from the singular behavior of the particle's effective polarizablity in the presence of a metal-dielectric-metal multilayer substrate. We show that this phenomenon is closely related to the existence of a flat-band plasmon mode supported by the multilayer substrate.

The interaction between Prof. Liu's students (in particular Qiang Wang) and my student (Meng Xiao) also led to some new interesting ideas. They showed that the geometric Zak phases can help to predict the existence of interface states between a metasurface and a substrate. By manipulating the property of the metasurface, we can further tune the excitation frequency and the polarization of the interface state. Results are published in Phys. Rev. B 93, 041415(R) (2016).

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

The enhanced optical forces due to particle-slab resonance can be further studied to see if it can be used to manipulate and move small deep-subwavelength particles. Our results also show that the particle-slab resonance can depend on the chirality of the particle. Whether this can be further developed into a technology that can be used to separate particles of different chirality would be worth investigating. Another interesting topic worth pursuing is the particle-slab resonance in a colloidal environment and the effect of additional external parameters such as external fields. It is also possible that the enhanced interaction can be used to collect light/wave energy or to promote the coupling of light from a high index substrate to air. Prof. Liu's group and my former student (now postdoc) Shubo Wang are working on the coupling of light through particle-slab interactions.

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)

As light sources such as lasers are readily available, it would be highly desirable if light could be used as an effective tool to detect and to manipulate very small particles. However, it is well known that if an object is very small in size compared with the wavelength of light, it does not scatter light efficiently and hence it is difficult for light to "see" or "move" very small particles, even though modern light sources can carry a lot of energy. The problem is that the interaction of light with a small particle is intrinsically very weak. The main finding of this research project is that the interaction of light with a small particle can become greatly enhanced at a particular frequency if we simply put the particle near certain specific substrates. The mechanism is a special resonance effect that has not been noted before. This resonance is neither of the particle, nor of the substrate, but a collective resonance of the whole system. Such enhanced interaction can be employed to detect small particles. It can also be used to obtain enhanced optical forces to move and separate small particles.

Part C: Research Output

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

(Please attach a copy of each publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.))

The Latest Status of Publications				Author(s) ***(bold** the authors belonging to the project teams and denote the corresponding author with an asterisk*)*	Title and Journal/ Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*						
2014				**S. B. Wang and C. T. Chan***	"Lateral optical force on chiral particles near a surface", Nat. Commun. 5, 3307.	2014	Yes	Yes	Yes
2015				**M. Xiao,** X.Q. Huang**, H. Liu and C. T. Chan***	"Enhancement of polarizabilities of cylinders with cylinder-slab resonances", Sci. Rep., 5, 8189.	2014	Yes	Yes	Yes
2016				**S. B. Wang and C. T. Chan***	"Strong optical force acting on a dipolar particle over a multilayer substrate", Opt. Exp., 24, 2235.	2017	Yes	Yes	Yes

2016				Q. Wang, **M. Xiao, H. Liu*,** S.N. Zhu, **C.T. Chan**	"Measurement of the Zak phase of photonic bands through the interface states of metasurface/photonic crystal", Phys. Rev. B 93, 041415.	2017	Yes	Yes	Yes

9. Recognized international conference(s) in which paper(s) related to this research project was/were delivered *(Please attach a copy of each delivered paper. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)*

Month/Year/ Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
August/2014 /San Diego	Chirality Enables Unusual Optical Force	SPIE "Optics + Photonics"	2014	Yes	Yes	No
August/2015 /San Diego	Optical force acting on metallic nanostructure	SPIE Plasmonics: Metallic Nanostructures and Their Optical Properties as a part of NanoScience+ Engineering, Optics & Photonics Symposium	2017	Yes	Yes	No
August/2015 /New York	Optical Force in Plasmonic and Metamaterial Systems	6th International Conference on Metamaterials, Photonic Crystals and Plasmonics	2017	Yes	Yes	No

10. Student(s) trained *(Please attach a copy of the title page of the thesis.)*

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Shubo Wang	Ph D in Nano Science and Technology	Sept/2009	Aug/2013
Xiao Meng	Ph D in PHYS	Sept/2010	Aug/2014
Xiaohan CUI	Ph D in PHYS	Aug/2014	On-going

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

Not applicable.