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The Research Grants Council of Hong Kong
NSFC/RGC Joint Research Scheme
Joint Completion Report

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

Part A: The Project and Investigator(s)

1. Project Title

Investigation of Antenna Design and Electromagnetic Compatibility in Radio-Frequency System-in-Package
射頻系統級封裝中天線的設計和電磁兼容問題研究

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof Kwok-wa LEUNG	Prof Jun Fa MAO
Post	Chair Professor	Chair Professor & Vice President
Unit / Department / Institution	Department of Electronic Engineering	Shanghai Jiao Tong University , PRC
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Co-investigator(s) *(with title and institution)*		

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	01-Jan-2014		
Project Completion date	31-Dec-2017		
Duration *(in month)*	48		
Deadline for Submission of Completion Report	31-Dec-2018		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. To investigate new compact high-performance AiPs and solve their electromagnetic-compatibility (EMC) and reliability problems;
2. To investigate the interference and interaction between the antenna-in-package (AiP) and RF circuit in a 3-dimendional (3D) radio-frequency system-in-package (RF-SiP) including hybrid effects of electromagnetic, thermal, and stress fields;
3. To build an RF-SiP platform for co-design of the antenna and RF circuit; and
4. To develop system-level measurement and testing techniques that determine the electrical and EMC characteristic of the AiP and RF circuit.

5.2 Revised Objectives

N.A.

6. Research Outcome

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

Since the project is about the AiP and RF-SiP, it is useful to investigate new antennas that can be conveniently integrated with microwave circuits. Therefore, a patch antenna ([1] of Part C) and two substrate-integrated DRAs ([2], [3] of Part C) have been studied in this project. The patch antenna is a dual-polarized antenna with an excellent port isolation of more than -30 dB and a bandwidth of more than 8% for each polarization. For the substrate-integrated DRAs, the first design is a dual-frequency antenna operating at 5.2 GHz and 24 GHz, with antenna gains of 3.93 dBi and 6.32 dBi, respectively. The second substrate-integrated DRA is a 2×2 circularly polarized antenna array at 60-GHz, with a measured antenna bandwidth of 15.9% and a peak measured antenna gain of 11.43 dBic.

The differential antenna allows a direct connection to an integrated circuit that deploys the differential-signalling technique to increase the signal-to-noise ratio. Two differential DRAs have been designed in this project. The first design ([4] of Part C) deploys a phase delay line. Its measured cross-polarization level is ~30 dB weaker than the co-polarized counterpart in the boresight direction. The second design ([5] of Part C) uses two parallel microstrip lines to obtain the differential operation. Its single element and 2×2 array have measured −10 dB bandwidths of

22% (2.22–2.77 GHz) and 18.7% (2.23–2.69 GHz), respectively. In addition, it was hoped to design an AiP for GPS application and therefore a GPS antenna using a cross-dipole antenna has been designed as a practice ([6] of Part C). It has a wide 3-dB AR beamwidth of over 230° and a 3-dB gain beamwidth of 150°. Other new DRAs have been also designed and presented in international conferences ([9]-[18] of Part C).

An AiP using a probe-fed rectangular hollow DRA has been investigated ([7] of Part C). Two AiPs with and without internal PEC boundaries have been designed. It has been found that their measured 10-dB impedance bandwidths are given by 11.3% (2.33–2.61 GHz) and 8.9% (2.36–2.58 GHz) for no-PEC-boundary and PEC-boundary cases, respectively. Both results entirely cover 2.4-GHz WLAN band. An RF amplifier has been integrated inside the hollow region of each DRA. It has been found that the measured S-parameters and realized antenna gains (> 4.30 dBi) of the two cases are similar to each other, regardless of having a PEC boundary or not. However, it has been seen that the cross-polar field of the PEC-boundary case is desirably much weaker than that of the no-PEC-boundary case. Also, a slot-fed rectangular hollow DRA operating at 2.4 GHz has also been investigated for the AiP design ([8] of Part C). The slot-fed hollow DRA has a −10-dB bandwidth of 20.6%, which is about the double of the bandwidth of the probe-fed counterpart. A compact transmitting module has been obtained by integrating this slot-fed DRA with an RF-SiP consisting of power amplifier and a filter. It has been measured that this transmitting module has a −10-dB bandwidth of 5.7% (2.38-2.52 GHz) with an overall gain of ~15.0 dB.

Also, the EMI between the AiP and LNA has been investigated [7]. It has been found that the near fields of the DRA affect the output of the LNA severely. It has been observed that to operate the LNA normally, the input power of the DRA should be lower than a threshold value. It has also been observed that by using the PEC boundary, the threshold value can be increased by ~25 dB and a more stable LNA output can be obtained.

The hybrid EM, thermal, and stress effect on the AiP and RF-SiP has been investigated. A two-stage amplifier was placed inside the hollow region of a hollow DRA. The powers of the first and second stages of the amplifier are 0.9 and 2.8 W, respectively. It has been found that the hybrid effect can be strong on the bonding wires that connect the RF-SiP to the antenna and provide the dc bias. The bonding wires can be broken when the temperature is very high.

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

This project have used the linearly polarized, circularly polarized, and dual-frequency DRAs for AiP designs. Today, the diversity antenna is commonly used in personal wireless communication systems to enhance the signal quality. Therefore, it is of great interest to develop the diversity AiP. To design a diversity AiP, we can fabricate two orthogonal excitation slots beneath the solid part of the hollow DRA. The two slots excite two degenerate modes of the DRA at the same frequency, giving a polarization-diversity AiP.

The pattern-diversity AiP can also be developed. However, it is more challenging to design a pattern-diversity antenna than for a polarization antenna. It is because it needs to excite two different modes (not two degenerate modes) to obtain different radiation patterns, but different modes generally have different resonance frequencies. This new research will need to identify two modes that have different radiation patterns but can be made to have the

same resonance frequencies by tuning the dimensions and dielectric constant of the DRA. It also needs to choose suitable feeding methods to excite the two modes effectively.

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)

With the rapid development of wireless communications, it has been a trend to integrate the antenna with an RF module, which is known as antenna-in-package (AiP). Using this approach, the wireless system can be made smaller in size, lower in cost, and more efficient in power consumption. Also, the RF system-in-package (RF-SiP) is becoming popular and some research works on the antenna-integrated RF-SiP (AIRF-SiP) have been done. In this project, new AiPs and AIRF-SiP have been studied.

In general, the antenna and circuit of AiP/AIRF-SiP designs are arranged horizontally or vertically. In this project, a third arrangement of placing the circuit inside the hollow dielectric resonator antenna (DRA) have been used. To obtain more accurate results, the hollow DRAs have been designed with the presence of the circuit.

The system-level measurement and testing techniques have been developed to study the electrical and EMC characteristics of the AiP and RF circuit. Also, the hybrid electromagnetic, thermal, and stress effect has been studied using the ANSYS software package. It has been found that the hybrid effect can affect the bonding wires of the RF-SiP significantly.

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)*						
[1] 2015				Mike W. K. Lee*, **K. W. Leung**, and Y. L. Chow	"Dual polarization slotted miniature wideband patch antenna," IEEE Trans. Antennas Propagat., Vol. 63, No. 1, pp. 353-357.	No	Yes	Yes	Yes
[2] 2016				**Yuxiang Sun*** and **Kwok Wa Leung**	"Substrate-integrated two-Port dual-frequency antenna", IEEE Trans. Antennas & Propagation, Vol. 64, No. 8, pp. 3692-3697.	No	Yes	Yes	Yes
[3] 2018				**Yuxiang Sun** and **Kwok Wa Leung***	"Circularly-polarized substrate-integrated cylindrical dielectric resonator antenna array for 60-GHz applications", IEEE Antennas and Wireless Propagat. Lett., vol. 17, No. 8, pp. 1401-1405.	No	Yes	Yes	Yes

[4] 2018				**Yuxiang Sun**, **Kwok Wa Leung*,** and **Jun-Fa Mao**	"Dualfunction dielectric resonator as antenna and phase-delay-line load: designs of compact circularly polarized/differential antennas", IEEE Trans. Antennas & Propagation, Vol. 66, No. 1, pp. 414-419.	No	Yes	Yes	Yes
[5] 2018				**S.-J. Guo, L.-S. Wu***, **K. W. Leung**, and **J.-F. Mao**	"Microstrip-fed differential dielectric resonator antenna and array", *IEEE Antennas and Wireless Propagat. Lett.*, vol. 17, No. 9, pp. 1736-1739.	No	Yes	Yes	Yes
[6] 2017				**Y.-X. Sun**, **K. W. Leung** and **K. Lu***	"Broadbeam cross-dipole antenna for GPS applications," *IEEE Trans. Antennas Propagat.*, Vol. 65, No. 10, pp. 5605-5610.	No	Yes	Yes	Yes
[7] 2018				**S.-J. Guo**, **K. W. Leung***, **J.-F. Mao**, and N. Yang	"A dielectric resonator antenna-in-package design and its electromagnetic interference investigation on amplifier" *IEEE Access*, vol. 6, issue 1, pp. 54994-55003.	No	Yes	Yes	Yes

[8]			In preparation		"A compact transmitter module with slot-fed dielectric resonator antenna", *IEEE Antennas and Wireless Propagat.*	No	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)*
[9] July/2015 Czech Republic	A dualband circularly polarized rectangular dielectric resonator antenna with L-shaped slots on the ground	Progress in Electromagnetic Research Symposium	Yes (2015)	No	Yes	Yes
[10] Nov/2015/ Hsinchu, Taiwan	Compact omnidirectional circularly polarized dielectric resonator antenna	International Workshop on Electromagnetics and R&S Student Competition	Yes (2015)	No	Yes	Yes
[11] Nov/2015/ Hsinchu, Taiwan	Wideband rectangular dielectric resonator antenna with polarization diversity	International Workshop on Electromagnetics and R&S Student Competition	Yes (2015)	No	Yes	Yes

[12] Nov/2015/ Hsinchu, Taiwan	Unidirectional circularly polarized dielectric resonator antenna for mirror integration	International Workshop on Electromagnetics and R&S Student Competition	No	Yes	Yes	Yes
[13] July/2015/ Vancouver, Canada	Bidirectional dielectric resonator antenna	IEEE Antennas and Propagation Society International Symposium	No	Yes	Yes	Yes
[14] June/2016/ Fajardo, Puerto Rico	Gain enhanced omnidirectional cylindrical ring dielectric resonator antenna	IEEE Antennas and Propagation Society International Symposium	No	Yes	Yes	Yes
[15] July/2017/ San Diego, USA,	Wideband circularly polarized cylindrical dielectric resonator antenna	IEEE Antennas and Propagation Society International Symposium	No	Yes	Yes	Yes
[16] Feb/2015/ Hong Kong	Gain enhanced omnidirectional rectangular dielectric resonator antenna	IEEE International Conference on Computational Electromagnetics	No	Yes	Yes	Yes
[17] Feb/2015/ Hong Kong	On a wideband circularly polarized dielectric resonator antenna using a higher-order mode	IEEE International Conference on Computational Electromagnetics	No	Yes	Yes	Yes
[18] Feb/2015/ Hong Kong	Wideband two-layer transparent cylindrical dielectric resonator antenna used as a light cover	IEEE International Conference on Computational Electromagnetics	No	Yes	Yes	Yes

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

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Yuxiang SUN	PhD, CityU	Aug. 1, 2013	Oct 2016 (PhD graduation)
Sheng-Jie GUO	PhD, Shanghai Jiao Tong University (Co-supervised at CityU by the PI from Nov 20, 2015 to Feb 20, 2017)	Sept. 9, 2013	April, 2019 (Expected PhD graduation; already offered a job by the 14th Institution of China Electronics Technology Group Corporation)

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

The following conference paper ([10] of Section C) was awarded the **Student Best Paper Award**:

L. Guo, W. W. Li, and **K W Leung**, "Compact omnidirectional circularly polarized dielectric resonator antenna," 2015 International Workshop on Electromagnetics: Applications and Student Innovation Competition, Hsinchu, Taiwan.