Project number: T42-103/16-N

RESEARCH GRANTS COUNCIL
THEME-BASED RESEARCH SCHEME (TRS)

Completion Report on Funded Project

Project start date: 01 January 2017
Project completion date: 30 June 2022

1. Project Title:

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)	CHAN Chi-hou/ Chair Professor of Electronic Engineering	Dept. of Electrical Engineering / State Key Laboratory of Terahertz and Millimeter Waves (SKLTMW)* /City University of Hong Kong (CityU)	12

Co-Principal Investigator(s)	PUN Edwin Yue Bun/ Chair Professor of Electronic Engineering	Dept. of Electrical Engineering / SKLTMW/CityU	8
	LUK Kwai-Man/ Chair Professor of Electronic Engineering	Dept. of Electrical Engineering /SKLTMW/CityU	4
	PANG Stella W. / Chair Professor of Electronic Engineering	Dept. of Electrical Engineering /SKLTMW/CityU	4
	SHAW Jeffrey/ Chair Professor	School of Creative Media /CityU	4
	LO Kenneth Kam Wing/	Dept. of Chemistry	4

	Chair Professor	/SKLTMW/CityU	
	VELLAISAMY Arul Lenus Roy/ Associate Professor	Dept. of Materials Science and Engineering /SKLTMW/CityU	4
	JARRAHI Mona/ Professor	Dept. of Electrical Engineering /University of California at Los Angeles	2*
	LIU Huiyun/ Chair Professor of Semiconductor Photonics	Dept. of Electronic and Electrical Engineering/ University College London	0*
	DECROZE Cyril/ Associate Professor	XLIM Research Institute and University of Limoges	4

Co-Investigator(s)	RENAUD Cyril / Reader /Associate Professor	Dept. of Electronic and Electrical Engineering/ University College London	0*
	TONG Kenneth Kin Fai/ Reader /Professor	Dept. of Electronic and Electrical Engineering/ University College London	4*
	QU Shi-Wei /Professor	School of Electronic Engineering / University of Electronic Science and Technology of China	6
	WONG Kenneth Kin Yip /Professor	Dept. of Electrical and Electronic Engineering/ The University of Hong Kong	2
	LEE Nikki Pui Yue/ Assistant Professor	Dept. of Surgery/ The University of Hong Kong	2
	LEUNG Kwok Wa/ Chair Professor of Electronic Engineering	Dept. of Electrical Engineering /SKLTMW/CityU	2
	CHAN Nelson Sze Chun / Professor	Dept. of Electrical Engineering /SKLTMW/CityU	2
	LEE Joshua En-yuan / Associate Professor	Dept. of Electrical Engineering /SKLTMW/CityU (left in 2021)	2
	Leung Shu Hung/ Associate Professor	Dept. of Electrical Engineering /SKLTMW/CityU	2^
	WONG Hang / Associate Professor	Dept. of Electrical Engineering /SKLTMW/CityU	4
	GAI Xin/ Assistant Professor	Dept. of Electrical Engineering /SKLTMW/CityU	2^
	WANG Cheng / Assistant Professor	Dept. of Electrical Engineering /SKLTMW/CityU	2
	WONG Alex Man Hon/ Assistant Professor	Dept. of Electrical Engineering /SKLTMW/CityU	2
	HO Johnny Chung Yin / Professor	Dept. of Materials Science and Engineering/SKLTMW/CityU	4
	LAM Yun Wah/ Associate Professor	Dept. of Chemistry/SKLTMW /CityU	2
	WONG Alex Chun Yuen/ Associate Professor	Dept. of Chemistry/ SKLTMW /CityU	2

Former Co-Principal Investigator	XUE Quan/ Chair Professor of Microwave Engineering	Dept. of Electrical Engineering /SKLTMW/CityU	Left CityU N.A. Reported in 3rd report

Former Co-Investigator	KIM Taejoon / Assistant Professor	Dept. of Electrical Engineering /SKLTMW/CityU ((this member was deleted from the team)	Left CityU N.A. Reported in 3rd report

Collaborators	N.A.	N.A.	N.A.

 # Please highlight the approved changes in the project team composition and quote the date when the 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.

3. Project Objectives

Summary of objectives addressed/achieved:

Objectives*	Percentage achieved	Remarks**
1. Develop low-cost and efficient THz sources and detectors based on both optical and microwave techniques	100%	1. An open-looped 0.35 THz CMOS radiator IC with an integrated antenna for linearly-polarized radiation. (Achieved, Deliverable 1 of Stage 2 Report) 2. Nano-antennas using GaAs nanowires instead of bulk GaAs. (Addressed, Deliverable 2 of Stage 1 Report, Deliverable 1 of Stage 3 Report, Deliverable 2 of this report) 3. A 0.35 THz CMOS radiator IC integrated with on-chip phase-locked loop for circularly-polarized radiation. (Achieved, Deliverable 1 of Stage 3 Report and Deliverables 1, 2 and 3 of this report) 4. Nano-antennas with 3D plasmonic contact electrodes combined with carbon photoconductors. (Addressed, Deliverable 2 of Stage 2 Report, and Deliverable 2 of this report) 5. Investigation and design of beam-steering 0.35 THz CMOS phased-array radiator IC with circularly-polarized radiation. (Achieved, Deliverable 1 of Stage 1 Report, Deliverable 1 of Stage 2 Report, Deliverable 1 of Stage 3 Report, and Deliverables 1, 2, 3, and 4 of this report) 6. THz source with increased optical-to-THz conversion efficiency through novel design with carbon nanoconductors and GaAs nanowires. Similar approach will be adopted for THz detector. (Addressed, Deliverable 2 of Stage 1 Report, Deliverable 2 of Stage 2 Report, Deliverable 1 of Stage 3 Report, and Deliverables 2 of this report) 7. Completion of 0.35 THz phased-array radiator IC with intrinsic beam steering. (Addressed, Deliverable 1 and beam steering demonstrated by Deliverables 3 and 4 of this report) 8. Integration of the THz emitter and detector with light source. (Addressed, Deliverable 2 of this report)
2. Develop electronic scanning techniques for fast image	100%	1. Metasurfaces that can perform 2-D frequency beam scanning. (Achieved, Deliverable 3 of Stage 1 Report) 2. Metasurfaces that allow control of polarization states of the transmitted and reflected fields. (Achieved, Deliverable 4 of Stage 1 Report, Deliverable 5 of Stage 2 Report, and Deliverable 8 of

Objectives*	Percentage achieved	Remarks**
acquisition		Stage 3 Report) 3. Design of orthomode transducer using metasurfaces to speed up THz radiation measurement. (Achieved, Deliverable 3 of Stage 2 Report) 4. Development of signal processing techniques for THz imaging. (Achieved, Deliverable 4 of Stage 2 Report, Deliverable 3 of Stage 3 Report, and Deliverables 4 and 6 of this report) 5. Demonstration of metasurfaces that allow lateral shift of focal points with varying frequency. (Achieved, Deliverable 3 of Stage 1 Report) 6. Demonstration of frequency beam scanning using nanoantennas. (Addressed, Deliverable 3 of Stage 1 Report and Deliverables 3 and 4 of this report) 7. Antenna array using novel controllable materials for beam forming. (Achieved, Deliverable 4 of this report)
3. Develop near-field measurement techniques to enhance image resolution	100%	1. Completion of an automatic near-field THz scanning system with probe compensation. (Achieved, Deliverable 5 of Stage 1 Report) 2. Design, fabrication and testing of high-gain THz antenna array. (Achieved, Deliverable 6 of Stage 1 Report, Deliverable 5 of Stage 2 Report, Deliverable 1 of Stage 3 Report, and Deliverable 1, 3 and 4 of this report) 3. Algorithm for image reconstruction using amplitude-only measurement data. (Achieved, Deliverable 4 in Stage 2 Report) 4. Completion of a THz measurement system that can perform Stokes' parameter measurement. (Achieved, Deliverable 5 of Stage 3 Report) 5. Computational of Mueller matrix from Stokes' parameter measurement for polarimetric imaging of cancer for ex-vivo characterization. (Addressed, Deliverable 5 of Stage 3 Report and Deliverable 5 of this report)
4. Develop display technology for and enhance the sensitivity of THz imaging	100%	1. THz probes that provide linearly- polarized, circularly-polarized and ±45°-polarized radiation for Stokes' parameter measurement. (Achieved, Deliverable 5 of Stage 2 Report) 2. Establishment of subcutaneous and orthotopic tumor xenograft models. (Achieved, Deliverable 6 of Stage 2 Report) 3. Development of photothermal and related techniques for enhancing the sensitivity of THz imaging. (Achieved, Deliverable 7 of Stage 2 Report and Deliverable 5 of this report) 4. Testing the ability of THz for cancer diagnosis using subcutaneous and orthotopic tumor xenograft models. (Addressed, Deliverable 6 of Stage 3 Report and Deliverable 6 of this report) 5. Monitoring of cancer treatment response with THz methods. (Addressed, Deliverables 6 and 7 of Stage 3 Report and Deliverable 6 of this report) 6. Studying of structural changes and substrate binding properties of proteins by THz spectroscopy. (Addressed, Deliverable 7 of this report investigated substrate binding properties)
5. Create libraries of THz spectral signatures of	100%	1. Investigation of chemicals and proteins that have fingerprint spectra in the THz region of interest. (Achieved, Deliverable 6 of Stage 2 Report, and Deliverables 5, Deliverable 6 of Stage 3 Report and Deliverable 7 of this report)

Objectives*	Percentage achieved	Remarks**
Chemicals and proteins		2. Collection of data for spectral signatures and power absorption for selected samples as identified in Stage 1. (Achieved, Deliverable 7 of Stage 1 Report, Deliverable 8 of Stage 2 Report, Deliverable 6 of Stage 3 Report and Deliverables 6 and 7 of this report) 3. Absorption characteristics of various chemicals by THz spectroscopy. (Addressed, Deliverable 7 of this report)

* *Please highlight the approved changes in objectives and quote the date when the 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.))

Terahertz Source Integrated Circuits: One of the best research accomplishments of the project is the development of high-power terahertz (THz) radiator integrated circuits (ICs) as THz sources for imaging and spectroscopy. In journal (J) papers J200, J214, J238, J247, and J275, and conference (C) paper C81, we systematically pushed the performance envelope of 65-nm complementary metal-oxide semiconductor (CMOS) technologies for terahertz sources using second- and third-harmonic generations. Exploiting our expertise in advanced antenna technologies, both on- and off-chip antennas, we reported in J214 the highest effective isotropic radiated power (EIRP) and highest dc-to-THz efficiency among silicon-based scalable THz sources beyond 400 GHz using a low-cost Teflon lens. In J238, we reported a ring-coupled oscillator-radiator array using a miniature patch antenna element. The design achieves an area efficiency of 0.66 mW/mm^2 at 472 GHz, the highest among THz radiator arrays using on-chip patch antennas. It also achieves the state-of-the-art dc-to-THz efficiency and frequency tuning range of 0.12% and 4.2%, respectively. The smaller chip size leads to a lower fabrication cost. In J247, we reported a 4×4 oscillator array with the unit cell comprising two oscillators with two slot antennas radiating the third-harmonic power. It has an area efficiency of 0.52 mW/mm^2 at 699 GHz. The designed array has the highest radiated power, radiated power per area, EIRP, frequency tuning range, and dc-to-THz efficiency among silicon-based scalable coherent radiator arrays operating beyond 600 GHz. A US patent US 11,670,862 B1 has been granted on this invention. J214 and J247 were published in the *IEEE Journal of Solid-State Circuits (JSSC)*, the top journal in IC designs. C81 was presented at the *IEEE International Solid-State Circuits Conference* 2023 (*ISSCC 2023*), which is regarded as the IC design Olympiad. In C81, we reported a 12×12 (144 elements) coupled-oscillator array that occupies a 2mm×1.7mm area. It can operate between 643 and 689 GHz with a tuning range of 6.9%. It radiates a peak power of 9.1dBm or 8.13mW with 3.32W power consumption, i.e., a 0.245% dc-to-THz efficiency at 675 GHz. It has an area efficiency of 2.39 mW/mm^2, the highest beyond 300 GHz. The corresponding lensless EIRP is 30.8 dBm, and the measured phase noise at 1MHz offset is -90.9 dBc/Hz. By changing the bias voltage to establish different phase gradients across the array, the beam can be steered from -45° to 45° in the H-plane. The extended version of the paper J275 has been submitted to *IEEE JSSC*. The output power of this THz is 1600 times that of our THz time-domain spectrometer and frequency-domain extension modules with a typical output power of 5μW. Imaging utilizing this high-power IC has been presented in the *Theme-based Research Scheme (TRS) Public Symposium* 2022 held on December 11, 2022 at the University of Hong Kong. (https://trs2022.hku.hk/)

We delivered the following invited and keynote presentations for our THz source ICs:

Haifeng Zhou, Shangcheng Kong, Kam-Man Shum, Liang Gao, and Chi Hou Chan, "A 320 GHz fully integrated beamsteering IC," the *14th Global Symposium on Millimeter-Waves & Terahertz*, May 18-20, 2022, Yonsei University, Seoul, Korea (30-minute presentation)

L. Gao and C. H. Chan, "High-power terahertz source in CMOS," the 22nd edition of the *National Microwave Days* in Limoges, France, June 7-10, 2022. Keynote Speaker (45 minutes). The theme of the conference is "Imaging and Millimeter and Terahertz Telecommunications".

L. Gao and C. H. Chan, "Terahertz radiator array chips," *Workshop on IC Advances in China*, June 22-24, Shenzhen, China (online). Keynote Speaker (40 minutes). The other keynote speaker was Professor Ruonan Han of MIT. There were over 2000 registrations for the workshop, and over 800 people were online during my presentation. All conference speakers must have paper(s) published in the *IEEE Journal of Solid-State Circuits (JSSC)* or *IEEE Solid-State Circuits Conference (ISSCC)* within two years.

Terahertz Lens Antennas Operating at 300 GHz: We exploited the Mueller matrix polarimetry for THz imaging to enhance image quality. For Mueller matrix image construction, one needs to perform 36 combinations of six incident and six receiving polarizations. These polarizations include horizontal, vertical, ± 45°, and left- and right-handed circular polarizations. The transmitting and receiving antennas are standard linearly-polarized (LP) pyramidal horns. We designed a lens capable of transforming the incident LP spherical wavefront from the horn into a transmitted circularly polarized (CP) planar one in the far-field region in J95 by exploiting low-cost 3D printing technologies. We invented a new printing approach that outperformed the printing quality achieved by that recommended by the manufacturer (FormLab) of the 3D printer. The lens' aperture phase distribution was modified so that the transmitted plane wave would be focused on the imaging target. The dielectric posts were employed as the pixel elements of the discrete dielectric lens (DDL), whose heights were tuned from pixel to pixel to realize the required aperture phase distribution. Based on this DDL approach, we proposed a novel nondiffractive Bessel beam launcher with 2D beam-scanning capability in J153. The launcher consists of two identical in-plane rotatable DDLs fed by a pyramidal horn. The two thin and lightweight DDLs can transform the quasi-Gaussian beam with a spherical phase front from the horn into a well-collimated, confined pseudo-Bessel beam. Simultaneous in-plane rotation of the two DDLs in the same and opposite directions can steer the generated Bessel beam in the azimuth and elevation plane, respectively. The 2D scanning nondiffractive Bessel beam has a large field of view of 86.2º and full azimuth coverage. It has applications in THz fast noncontact detection, tracking, and imaging systems. We reported a DDL antenna with orbital angular momentum (OAM) mode reconfigurability in J156. The antenna consists of a stationary lower DDL and an upper in-plane rotatable DDL, fed by a stationary pyramidal horn. The DDL pair can transform the quasi-Gaussian beam from the feed source into vortex waves, and its OAM mode number, l, can be dynamically reconfigured among l = 0, ±1, and ±2 by a simple mechanical in-plane rotation of the upper DDL with specific angels relative the stationary lower one. The THz line-of-sight link experiments showed that the mode isolations are better than 15, 13, and 10 dB when the OAM modes of the DDL antennas are in l = 0, ±1, and ±2, respectively. Conventional vortex beams carrying OAM suffer from the limitation of beam divergence. Novel 3D-printed DDLs for generating nondiffractive OAM beams were reported in J186. The DDL can combine the functionalities of three conventional bulky refractive hyperbolic, spiral phase plane, and aixcon lenses. Two DDL synthesis methods were explored to cover the OAM signal in an intended longitudinal region,. The first approach is based on geometric optics, and the second uses the alternating projection method to optimize the aperture phase distribution of the DDL. The generated higher-order Bessel beam and extended higher-order Bessel beam can overcome convention vortex beams' divergence, greatly promoting the practical applications of OAM waves in wireless communications and imaging. In J253, we introduced a novel near-field focus lens antenna with 3D focus-steering capability. It consists of a pair of thin DDLs placed above a stationary feed horn. The DDL doublet's in-plane synchronous counter-rotation and co-rotation could scan its focus radially and azimuthally, respectively. The separation between the DDL doublet controls the focal point along the longitudinal direction. The reported 3D focus-scanning antenna has a large FoV of 72º, opening new avenues for fast 3D THz imaging applications. In J262, published in *Science Advances*, we reported the synthetic phase design of rotary doublet Airy beam and triplet Gaussian beam varifocal 3D-printed meta-devices to fully control the THz beam propagation direction and coverage. Airy beams' diffraction-free, self-healing, self-accelerating properties were demonstrated to enable signal transmission stability and security in wireless communications. At the same time, the triplet meta-device was used to focus the Thz wave to an arbitrary position in 3D space. These devices can benefit future 6G communications, wireless power transfer, zoom imaging, and remote sensing. We contributed a book chapter on THz Lens Antennas in the Antenna and Array Technologies for Future Wireless Ecosystems (edited by Jay Guo and Rick Ziolkowski) published by IEEE Press/Wiley in 2022. Our THz OAM DDL antennas for 5G and beyond were summarized in J243 published in *IEEE Communications Magazine*.

Terahertz Wave Manipulations: We developed THz devices for beam steering and focusing by dispersion engineering, i.e., variation of wave propagation with frequency. In J10, we demonstrated the flat THz reflective metasurface design with scanning ability. The focal point can be steered horizontally across or vertically away from the reflective surface. We also provided a conceptualized scheme such that focusing scanning beam in a 3D space can be achieved. The frequency-controlled focus scanning was extended into 2D in J82. The first design can rotate the focal points in a circular path from 225 to 300 GHz. The second design is a dual-band reflectarray with 1D scanning in each operating band with different focal positions along the direction orthogonal to the scanning. The dual-band frequencies range from 220 to 260 GHz and 370 to 430 GHz. In J107, we reported THz frequency-selective surface (FSS) with polarization selection and conversion characteristics. The same FSS can provide transmission and polarization conversion at different THz frequencies. The LP incidence is converted into RHCP at 430 GHz and LHCP at 890 GHz. Transverse electric and transverse magnetic incidences are transmitted at 630 GHz with a minimum insertion loss of 0.36 dB. In J155, we reported active meta polarizers based on a phase-change material, vanadium dioxide. The meta polarizer can independently manipulate the polarization of the incident THz waves in two orthogonal directions. It can also perform as a highly efficient reflector at the same frequencies. All these can be conveniently manipulated with DC bias. In J228, we reported a 3D microstructured FSS using carbon-based polyimide as a precursor to enhance the resonant frequency at the THz range. Gold nanoparticles (AuNPs) are embedded on 3D microstructured carbonized polyimide (3D-CPI) film to improve their FSS property through plasmonic effects. 3D-CPI FSS film shows band-stop filter properties in the frequency range of 0.5–1.5 THz and with a maximum return loss (RL) of 40.5 dB (at the resonant frequency of 1 THz). The 3D-CPI/AuNPs film demonstrates the highest RL of 43.7 dB at the higher excitation resonance frequency ≈1.06 THz due to the interaction of plasmonic electrons with scattered delocalized electrons in carbon, which induces the mechanisms for EMI shielding. These films can be used as an EMI shielding material for THz measurement equipment.

Terahertz Antennas and Circuits: We reported wide impedance-bandwidth and gain-bandwidth THz on-chip antenna with chip-integrated dielectric resonator fabricated by 65nm CMOS technology in J193. It has a peak gain of 8.6 dBi and a maximum radiation efficiency of 44% at 295 GHz. The -10dB impedance bandwidth and 3dB gain bandwidth are 50% and 34.5%, respectively. This on-chip antenna has the widest bandwidth at THz frequencies. In J195, we presented THz CP and LP leaky-wave antennas based on spin-orbit interaction of spoof surface plasmon polaritons (SPPs). The LP leaky-wave antenna was fabricated and experimented. It achieves 14.5–17.5 dBi gain and scans from −18° to +12° in the operating frequency band of 145–220 GHz with $|S11| < -10$dB. In J218, we developed THz wideband and miniaturized SPP load made of Ni metal. The SPP load can achieve $|S11| < -20$ dB from 195 to 500 GHz and a miniaturized size of 1.7 $\lambda g \times 0.23\ \lambda g$ at 300 GHz. By integrating with the proposed SPP load made of Ni, a two-way Goubau-line power divider was demonstrated to validate the load's utility in THz multiple-port planar circuit application on a thick substrate. This load can serve as broadband THz termination for THz circuitries. In J245, we reported a single-layer planar Goubau-line antenna with endfire radiation based on substrate mode. The proposed THz antenna was fabricated and measured, which can operate in a 325–500 GHz band with endfire radiation and achieve 8.5–11.3 dBi gain. In J265, we demonstrated THz SSPP logic gates "OR/AND," "XOR/NOT," and "NAND," operating from 220 to 320 GHz. Both simulated and experimental results verified that these logic gates could be realized. The spoof plasmonic logic circuits are realized on a planar platform, promising on-chip integration with THz circuits. Planar multifunctional THz plasmonic devices based on the interaction between SSPPs and spoof localized surface plasmon (SLSPs), including the functions of pass-through transmission, multifrequency resonances, and phase shift, were proposed and experimentally demonstrated in J267. Such a THz plasmonic device will open many possibilities to reduce the circuit size in THz ICs. In J215, we demonstrated a compact and high-efficiency THz folded metasystem consisting of two metasurfaces comprising high-resistivity Si material. The folded architecture can miniaturize the THz system, and the THz source/detector can be directly integrated as a single unit. The bottom metasurface uses the dielectric resonator to eliminate the ohmic loss. The upper metasurface utilizes the Bragg reflection to replace conventional metallic linear polarizers. The folded metasurface was fabricated by the photolithography and deep reactive ion etching (DRIE) of Si wafers. The measured peak gain is 33.4 dBi at 1.08 THz. The measured 3dB gain bandwidth is about 7% from 1.024 to 1.1 THz. A THz reflective metausurface was reported in J261 for frequency-controlled Bessel beam steering. The metasurface prototype operating from 0.8 to 1.1 THz was fabricated and experimentally demonstrated for Bessel beam generation and beam scanning from 6.4° to 15.2° off normal. J246 presented a systematic investigation of the millimetre-wave-optic modulation performances of thin-film lithium niobite modulators at frequencies up to 325 GHz. A measured 3-dB electro-optic bandwidth of 170

GHz and a 6-dB bandwidth of 295 GHz were achieved. The work paves the way toward future integrated THz-photonic systems for beyond 5G communications and radar applications. With the THz planar antenna's adoption, the system can be made wireless. This led to a funded GRF project entitled "An integrated millimeter-wave photonic phased array receiver system" awarded to Dr. Cheng Wang.

Innovative Wave Synthesis for Beam Forming and Imaging: In J188, we reported a new antenna design coined the amplitude-modulated (AM) leaky-wave antennas, borrowing the idea of amplitude modulation from classical communications theory. The traveling wave in a wave-guiding structure serves as the carrier wave whose amplitude is spatially modulated by a predefined modulating waveform to generate the desired modulated waves. We can synthesize the AM antenna structure based on the desired radiation pattern. The synthesis approach is general, but the fabrication depends on the operating frequency. To demonstrate the AM leaky-wave antenna at 30 GHz, the leaky-wave antennas in terms of corrugated transmission lines were fabricated by computer numerical control (CNC) machining. The first antenna is a sinusoidally AM leaky antenna to yield far-field radiation at 45º off-normal at 30 GHz with a gain of 15.7 dBi. The beam can scan from -5º to 63º from 24 to 31 GHz. The second antenna has a flat-top radiation pattern from 35º to 65º. The measured gain of the antenna s 7.4 dBi. A US patent US 11,611,149 B2 has been granted. In J244, the synthesis approach was extended to THz frequencies. The sinusoidally modulated corrugated transmission line was replaced by periodically perforated air holes of different sizes in a quartz substrate fabricated by DRIE. Beam scanning along the length of the antenna from -5º to 25º was achieved experimentally by varying the frequency from 0.95 to 1.05 THz. 2D arbitrary direction deflection and focusing were demonstrated by simulations. These AM leaky-wave antennas, once fabricated, the radiation characteristics would be fixed. We developed a sideband-free space-time-coding metasurface antenna in J252, published in *Nature Electronics*, to flexibly synthesize and manipulate the radiation characteristics through software control. The paper reported a 1-bit space-time-code metasurface antenna that can extract and convert guided waves into desired free-space waves in space and frequency domains. The waveguide-integrated metasurface antenna also provides a self-filtering phenomenon that overcomes the issue of sideband pollution found in traditional spatiotemporally modulated metasurfaces. The slot array on a substrate-integrated-waveguide transmission line is periodically loaded with microwave switches. Upon controlling these switches' ON/OFF spatial and temporal sequences, we can demonstrate high-efficiency frequency conversion, fundamental-frequency continuous beam scanning, and independent control of multiple harmonics. Incidentally, for beam steering, the spatial distribution of the ON/OFF switches resembles a sinusoidal function. The periodicity of the sinusoidal function dictates the beam direction, as in J188 and J244. In J274, just accepted in principle by *Nature Communications*, the slot array was modified such that we can also manipulate the polarization of the radiation. Therefore, the five characteristics of our invented metasurface antenna's radiation in polarization, amplitude, frequency, direction, and phase can all be software controlled. By altering the space-time coding, we can synthesize radiation characteristics such as far-field beam steering, near-field beam focusing, multiple beam radiation, near-field focal point scanning, etc. We have demonstrated the use of this antenna for real-time microwave imaging at 24 GHz. The bottleneck of extending the applications to THz frequencies is lacking of commercially available switches that can operate at THz frequencies. We are currently experimenting with the idea of THz IC implementation.

We delivered the following keynote presentation for our THz antennas:

Chi Hou Chan, "THz research at State Key Laboratory of Millimeter Waves, Partner Laboratory in City University of Hong Kong," Keynote Speech, IEEE International Workshop on Electromagnetics 2017 (iWEM 2017): Applications and Student Innovation Competition, May 30th – June 1, 2017, University College London, London, UK.

C. H. Chan, "Terahertz Antennas – Design, Fabrication and Measurement" Keynote Speech, 2018 International Workshop on Antenna Technology (iWAT), March 5-7, Nanjing, China.

C. H. Chan, "Millimeter-wave & terahertz antennas for 5G and beyond," 2018 Hauwei Strategy and Technology Workshop (STW), May 15-17, 2018, Shenzhen, China (invited)

C. H. Chan, "THz antennas – design, fabrication and testing," 13th European Conference on Antennas and Propagation, EuCAP2019, Krakow, Poland, March 31-April 5, 2019. Article number 8739871. (40-minute invited paper)

Chi Hou Chan, "Terahertz Antennas for 6G and Beyond – Design, Prototyping, and Characterization," One-hour Keynote Speech, 2022 Fifth IEEE International Workshop on Mobile Terahertz Systems (IWMTS), 4-6 July 2022, Duisburg, Germany, hybrid workshop.

Frequency- and Time-Domain THz Imaging: In J125, we demonstrated THz imaging at 300 GHz by building the imaging system with a network analyzer and frequency extension modules for both transmission and reflection modes. We developed the DDL lenses for Mueller matrix polarimetry and polar decomposition as the required THz lenses were not commercially available. The structural similarity index measure (SSIM) indicates the image's goodness. The SSIM values for the Mueller matrix could reach as high as 0.9-0.98 for the leaf sample (transmission mode) and 0.9 for the indium tin oxide (ITO) (reflective mode), respectively. The raw polarization images could only stabilize at 0.7-0.9 for the leaf and 0.2-0.4 for the ITO target. The SSIM value for the decomposition parameters for the latter could reach nearly 1, the maximum value and best image quality. In general, a minimum of 16 combinations of intensity-only measurements involving both LP and CP are required to completely and accurately determine the 4×4 Mueller matrix and comprehensively describe the polarization properties of the sample. However, broadband CP polarizers are rather difficult to achieve. In J183, a 3×3 Mueller matrix was contructed for the characterization of non-depolarizing samples. The multi-spectral 3×3 Mueller matrix polarimetry system based on the THz time-domain spectroscopy (TDS) was established from 0.1 to 1 THz. The polar decomposition in J125 was modified to explore the fine details and properties of the sample. By signal post-processing techniques, the Mueller matrix elements in the time domain were retrieved, and the time dimension reflecting the depth information facilitated the 3D reconstruction of the sample. Wideband LP polarizers were designed, fabricated, and incorporated into the TDS system. Since the TDS has phase information, CP imaging data can be computed from the LP, achieving wideband 4×4 Mueller matrix imaging. In J273, we reported a thin-film CP polarizer consisting of three metal-grid layers to be used in tandem with a photoconductive antenna (PCA) to generate THz CP radiation. The measured transmission loss of the polarizer is 0.86 dB at the design frequency of 0.8 THz. The minimum measured transmission loss is around 0.21 dB at 0.85 THz. The tri-layer CP polarizer's measured 3dB axial ratio bandwidth is 54.7% from 0.57 to 1 THz. We also developed THz hologram using the DDL technique developed for lens antennas. In J140, presented 3D printed hologram for THz imaging based on a diffractive neural network (DNN). Target imaging letters "THz" with uniform field amplitude were assigned to a predefined imaging surface. The entire training process took only 60s. The full-wave simulation and experimental results demonstrated the capability of the proposed hologram to achieve high-quality imaging in the THz regime. A deep-learning enabled DDL reconfigurable THz hologram is reported in J227. The hologram comprises two cascaded DDLs designed based on a diffractive deep neural network (D2NN). When fed by a 300 GHz THz horn, the hologram achieved dynamic holographic imaging by a simple mechanical translation of the perfect electric conductor mask attached to the first DDL. The hologram achieved reconfiguration in the absence of tunable components at high frequencies. To enhance the optical-to-THz conversion efficiency of PCA, we studied the use of novel materials such as graphene and semiconductor nanowires for the PCAs. One example is the high-mobility Indium Gallium Antimonide nanowires reported in J87 and published in *Nature Communications*. InGaSb nanowires (NWs) have the tunable bandgap, record-high hole mobilities and ultrabroad band, and ultrafast photoresponse from visible all the way to the infrared optical communication region (1550nm). For example, for the optimized $In_{0.28}$ $Ga_{0.72}Sb$ NW devices, they show broadband photodetection performance at room temperature, with a responsivity of $6000AW^{-1}$, specific detectivity of 3×10^9 Jones, external quantum efficiency (EQE) of 4.8×10^6 % and response time of 38 μs under IR illumination (1550nm) at a bias voltage of 2V. This efficient response in the tens of microsecond range represents one of the fastest responses among all NW IR photodetectors reported in the literature. This performance breakthrough was attributed to the enhanced chemical vapor deposition synthesis of these long, uniform, thin, stoichiometric InGaSb nanowires with improved crystallinity. More importantly, these NWs can be fabricated into NW parallel arrays-based devices, demonstrating their technological potential as active materials for many large-scale device applications. These nanowires would open up next-generation electronic and optoelectronic device application domains, including high-performance transistors, terahertz devices, etc.

Transition Metal Complexes as Biological Probes for Optical and THz Spectroscopy: It is well known that glucose is important for cancer cell metabolism. As described in J124, we have studied the luminescence and cellular uptake of an iridium(III) glucose complex [Ir(bt)$_2$(bpy-glucose)](PF$_6$). The THz spectra of human esophageal squamous carcinoma KYSE-450 cells incubated with the complex display a strong absorption peak at 1.2 THz, which is not seen in the spectra of untreated cells. Additionally, we have performed ICP-MS analysis to examine the biodistribution of the complex in mice bearing KYSE-450 xenografts. The results indicate that the complex was accumulated in the tumor. In J15, we have also reported two ruthenium(II) fructose complexes [Ru(N^N)$_2$(bpy-fructose)](PF$_6$)$_2$ (N^N = Ph$_2$-phen, bpy). Notably, the Ph$_{2\text{-phen}}$ complex was enriched in the plasma membrane of cancerous HeLa and MCF-7 cells by binding to the overexpressed GLUT5 on the cell surface. Furthermore, in J11, we have developed three iridium(III) phenylboronic acid (PBA) complexes [Ir(N^C)$_2$(bpy-TEG-PBA)](PF$_6$)·$_n$HCl (HN^C = Hppy, Hpq, Hpqa) to label sialic acids, which are overexpressed on the plasma membrane of cancer cells. The specific recognition of membrane-bound sialic acid residues by the pqa complex allows the differentiation of cancerous HepG2 cells from non-cancerous HEK-293T cells. Another typical cancer marker is the overexpression of glutathione (GSH), which plays an important role in many biological processes. In J98, we have described the photophysical and photochemical properties of a rhenium(I) perylene diimide (PDI) complex [Re(Ph$_2$-phen)(CO)$_3$(py-SS-PDI-TEG)](CF$_3$SO$_3$) and three benzoperylene monoimide (BPMI) complexes [Re(N^N)(CO)$_3$(py-CONH-C3-BPMI)](CF$_3$SO$_3$) (N^N = biq, Ph$_2$-phen, Me$_4$-phen) which serve as new cellular reagents for bioimaging, sensing, and photodynamic therapy (PDT) applications. We have also reported in J97 two iridium(III) polyethylene glycol (PEG) complexes with a disulfide linkage [Ir(N^C)$_2$(bpy-SS-PEG)](PF$_6$) (HN^C = Hpqe, Hpq) and a bimetallic iridium(III)–rhenium(I) complex [Ir(pqe)$_2$(bpy-SS-py)(CO)$_3$(Me$_4$-phen)Re](PF$_6$)(CF$_3$SO$_3$). Cell-based assays on the pqe complex demonstrated that the addition of GSH to induce cleavage of the disulfide linkage generated a more cytotoxic agent due to the release of the PEG pendant. As reported in J23 and J199, we have introduced a 2,4-dinitrophenyl (DNP) quencher to iridium(III) [Ir(pq)$_2$(N^N)](PF$_6$) (N^N = bpy-dinitro1, bpy-dinitro2, bpy-dinitro3) and rhenium(I) complexes [Re(N^N)(CO)$_3$(py-DNPS)](CF$_3$SO$_3$) (N^N = bpy-tosylamide, Me$_4$-phen, Ph$_2$-phen, phen) via a thiol-sensitive linkage for bioimaging and PDT. Bioorthogonal chemistry is a versatile pretargeting approach for cancer diagnosis and therapy. In J59, we have exploited the environment-sensitive emission properties of iridium(III) sydnone complexes [Ir(N^C)$_2$(bpy-CH$_2$-NHCO-C$_6$H$_4$-sydnone)](PF$_6$) (HN^C = Hdfppy, Hppy, Hpqe) to report their strain-promoted sydnone–alkyne cycloaddition (SPSAC) reaction with the strained alkyne bicyclo[6.1.0]non-4-yne (BCN). In J148, we have developed rhenium(I) sydnone complexes [Re(N^N)(CO)$_3$(py-syd-ph)](CF$_3$SO$_3$) (N^N = phen, Me$_4$-phen, Ph$_2$-phen) as phosphorogenic bioorthogonal probes to increase the signal-to-noise ratio. The SPSAC ligation of the complexes with BCN-modified ceramide and morpholine derivatives could specifically label the mitochondria and lysosomes, respectively. The THz-absorption properties of the sydnone-containing compound Br-syd-ph in the range of 1.2 – 6.0 THz show promising potential as THz probes. It appears that the strong absorption feature at ca. 3.5 THz is associated with the mesoionic ring of the molecule. In J143, we have developed four iridium(III) nitrone complexes [Ir(N^C)$_2$(bpy-nitrone)](PF$_6$) (HN^C = Hbt, Hbsn, Hdbq, Hdbpz) as phosphorogenic bioorthogonal probes. The combined use of a BCN-modified benzylguanine substrate and the SNAP-tag technology allows the complexes to target different subcellular locations for imaging and $^1O_2$-photosensitization. Additionally, we have measured the THz spectra of the nitrone compounds. The relatively prominent absorption at ca. 2.6, 2.8, 4.5, 4.8, and 5.5 THz in both the spectra of the ligand and complex should arise from the dipolar nature of the nitrone. In J2, we have developed three iridium(III) pyridyl-tetrazine complexes [Ir(N^C)$_2$(py-Tz-Me)](PF6) (HN^C = Hdfppy, Hppy, Hpq), and examined their photophysical properties, bioorthogonal reactivity, cellular uptake and localization. The results indicate that the direct coordination of a pyridyl-tetrazine derivative to a transition metal center can confer activatable emission properties on the tetrazine compound and enhance its reactivity toward dienophiles. In J180, we have developed four iridium(III) tetrazine complexes [Ir(N^C)$_2$(bpy-Tz-Ph)](PF$_6$) (HN^C = Hbt, Hbsn, Hdbq, Hdbpz) for bioorthogonal imaging and PDT. The complexes displayed more intense and longer-lived emission and higher $^1O_2$-generation efficiencies upon reaction with BCN than with trans-cyclooctene (TCO), indicative of bioorthogonal control of the emission and $^1O_2$-photosensitization properties of tetrazine complexes by the use of different reaction partners. In J226, we have modified three iridium(III) complexes with two tetrazine units [Ir(dptz)$_2$(N^N)](Cl) (N^N = en, Ph$_2$-phen, biq) for bioorthogonal labeling, bioimaging, PDT, and cargo delivery applications. Bioconjugation is a valuable method for labeling specific biomolecules with functional entities, making them useful for diagnostic and therapeutic applications. In J159, we have designed iridium(III) perfluorobiphenyl (PFBP) complexes [Ir(N^C)$_2$(bpy-PFBP)](PF$_6$) (HN^C = ppy, ppy-CH$_2$OH, pppy, pppy-CH$_2$OH, pq, pq-CH$_2$OH) for site-specific modification of the cysteine residue of the π-clamp sequence (FCPF). Related rhenium(I) PFBP complexes [Re(N^N)(CO)$_3$(py-PFBP)](CF$_3$SO$_3$) (N^N = phen, Me$_4$-phen, Ph$_2$-phen) have also been used to produce photofunctional peptide conjugates for cellular imaging, $^1O_2$-photosensitization, and enzyme sensing, as reported in J207. Furthermore, in J241, we have developed three near-infrared-emitting iridium(III) methylsulfone complexes [Ir(bpz)$_2$(N^N)](PF$_6$) (N^N = bpy-btz, bpy-mstp, bpy-odz) as sulfhydryl-specific reagents for peptide and protein modification. The resultant bioconjugates showed cancer-selective photocytotoxicity. Polyhedral oligomeric silsesquioxanes (POSSs) are a class of nanosized molecules with well-defined molecular formulas and structures. In J89, we have synthesized and characterized three new luminescent molecular hybrids with eight iridium(III) complexes grafted on a POSS unit [POSS-{Ir(N^C)$_2$(py-im)}$_8$](PF$_6$)$_8$ (HN^C = Hppz, Hppy, Hpq) to reduce dark cytotoxicity and photocytotoxicity. Furthermore, in J192, neutral iridium(III) POSS complexes [Ir(N^C)$_2$(L1-POSS)] (HN^C = Hppy, Hbt, Hbsn) were synthesized and characterized. The complexes were specifically localized in lipid droplets (LDs) upon cellular uptake, which allows the study of various LDs-related biological events. In J208, we have also designed three iridium(III) POSS complexes [Ir(pqe)$_2$(N^X)](PF$_6$)$_n$ (N^X = mbpy-POSS, n = 1; pic-POSS, n = 0; picpy-POSS, n = 1) as efficient theranostic agents that displayed tunable organelle-targeting properties, minimal dark cytotoxicity, and substantial photocytotoxicity even under hypoxic conditions.

6.2 What was the added value of the TRS 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?)

The TRS funding is paramount to the research infrastructure of this project. Although all major pieces of equipment were provided by the State Key Laboratory of Terahertz and Millimeter Waves, purchasing accessories, device fabrications, and biological and chemical samples were essential to advance THz imaging and spectroscopy. Through the long-term support of the TRS, we were able to take a system approach to the proposed research. The duration of typical GRF and CRF projects is too short, and their scale is small to accommodate the scope of the TRS project. We could not build the THz systems with existing components, rectify their deficiencies, improve their performances, etc., in the 3 year duration of the GRF and CRG schemes. With the goal of building a system, we were able to divide the project into different tasks and generate new research outputs. These new research outputs also formed the basis for further funded projects, including many new General Research Fund (GRF) projects, one Collaborative Research Equipment Grant, and one Collaborative Research Project Grant. An Area of Excellence Scheme Project, *Advanced Antenna Technology for a Smart World*, has been invited for an interview, and the final result will be officially announced in mid-July 2023. AoE was awarded on July 13, 2023.

For an imaging system, antennas are used for THz radiation and receiving the power transmitting through or reflecting from the imaged object. Therefore, we designed THz antennas that meet our needs, as illustrated in Section 6.1. We also needed to characterize the antenna's radiation patterns. For that, we built a single robotic arm near-field/far-field system. The experience and results gained led to a funded CRF Equipment Grant, "*High-Resolution Antenna Measurement System with Robotic Arms for Millimeter-Wave Frequencies*". This system has two robotic arms operating up to 500 GHz. Also stated in Section 6.1, we developed a THz radiator chip with two-order of magnitude higher output power than our commercially available imaging equipment. The tiny chip also replaced our imaging systems' bulky THz extension modules in frequency-domain measurements and the laser source in time-domain measurements. However, the chip is only a THz source, it does not have the baseband signaling capability for future 6th Generation (6G) wireless communications. Again, the experience and outputs gained from the THz radiator chip led to a funded CRF Project Grant, "*An Enabling Technology for 6G Wireless Communications*". As metasurface antennas and reconfigurable intelligent surfaces are some of the important technologies for 6G, our works on beam steering, beam focusing, and wave manipulation presented in Section 6.1 also laid the foundation for some of the proposed research in the AOE proposal.

The TRS funding grants also supported vast development opportunities and excellent training programs to supplement postdoctoral and undergraduate students in addition to mentoring junior faculty members. Dr. Cheng Wang is a Harvard trained expert on thin-film lithium niobate for optoelectronic applications. He was invited to take part in the TRS after he joined City University of Hong Kong. As stated in Section 6.1, he successfully modulated 300 GHz signal onto the optical carrier frequency. The THz antenna technologies developed in TRS also supported him for his GRF on integrated millimeter-wave photonic phased array receivers, extending his expertise to millimeter-wave/THz photonics. Dr. Wang received the inaugural Young Collaborative Research Grant, "*Large-Scale Lithium Niobate Photonic Integrated Circuits for Neuromorphic Computing*," as the Project Coordinator.

6.3 If the project has not met its original objectives, why?

The original objectives have been mostly met. In the original proposal, we have the five research tracks, namely, (i) THz Source and Detector, (ii) THz Beam Scanning Devices, (iii) THz Image Processing and Display, (iv) Biosensing and Spectroscopy, and (v) System Integration. For the THz source and detector, we worked on both THz radiator ICs and photoconductive antennas. We made excellent second- and third-harmonic THz radiator ICs as described in Section 6.1. We also developed a 540 GHz receiver with a third-order subharmonic mixer, with results presented in the *TRS Public Symposium* 2022. It has been demonstrated as a real-time detector for monitoring the moisture of a piece of wet cloth. This receiver IC can be used to replace the spectrum analyzer used in our high-power imaging system. When our THz source and receiver are designed at the same frequency, we will have a compact system for imaging. When several ICs with different frequencies are used, we can also build a compact system for spectroscopy. To enhance their performance, we have developed phototconductive antennas with graphene and GaAs nanowires. We have also developed wideband LP and CP polarized for Mueller matrix imaging. These photoconductive antennas were used as THz source and detector in our THz TDS system. We developed both passive and active THz beam scanning and wave manipulation. In particular, the beam scanning radiator IC operating at 675 GHz represents a major achievement of the project. On the other hand, the software-controlled metasurface antennas, reported at microwave frequency, will greatly impact if their operating frequency can be scaled up to that of 6G. We have developed Mueller matrix imaging and polar decomposition to enhance image quality. We also developed augmented reality software to display the measured antenna radiation patterns together with the measurement facility. Same display was employed for images of a zebra fish at different frequencies together with the THz TDS system. For biosensing and spectroscopy, we developed an array of transition metal complexes as biological probes for optical and THz spectroscopy, as detailed in Section 6.1. We also retrieved the electrical properties, namely, dielectric constant and loss tangent for a wide range of substrate and 3D printing materials that can be used for THz antennas and circuits. Given that the funded amount of the TRS was less than 50% of the originally requested amount, we did not intend to build a compact system. Nevertheless, we have demonstrated that a compact system can be built based on the THz source and detect ICs we have successfully designed, fabricated, and tested.

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

(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)

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)*
Please refer to the Appendix II for the details.						

(c) 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.

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

The TRS involved many investigators both locally and internationally. Due to the social disturbance followed by the Covid-19 pandemic, some international collaborations became quite difficult as international travels were not possible. Nevertheless, we managed to have fruitful joint publications with the University College London, the University of Limoges, and the University of Electronics Science and Technology of China. We supported the experimental validation of a new wideband millimeter-wave trapped surface wave propagation system for signal broadcast and jointly worked on THz OAM mode-reconfigurable lenses. They are also partnering with us on the Area of Excellence project proposal. For the University of Limoges, we first collaborated on THz imaging and later extended to reconfigurable THz metasurfaces with other experts on functional materials. This collaboration led to new projects on THz devices. We have many joint papers with the University of Electronics Science and Technology of China on THz metasurfaces. The collaboration extended to optical phased arrays funded by the Natural Science Foundation of China. Some outputs, e.g., arbitrary optical wavefront shaping and all-plasmonic optical leaky-wave antenna with low side-lobe level, were based on the AM modulation leaky-wave antenna methodology we developed in the TRS. We are still working on joint papers with UCLA as additional PCA samples are needed for performance comparison. Our THz IC experience led to a funded joint CRF project with Hong Kong University together with the University of Macau.

6.6 Research students trained (registration/awards):

Name	Degree registered for	Date of registration (DD/MM/YYYY)	Date of thesis submission/ graduation (DD/MM/YYYY)
Please refer to the Appendix III for the details.			

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

We have developed both near- and far-field platforms for THz antenna/metasurface/IC radiation measurements for this TRS using equipment available in the State Key Laboratory of Terahertz and Millimeter Waves. Photos of these measurement platforms were included in our published journal papers. All the linear and rotational movements are software control. We have proprietary software developed for data communication among different pieces of equipment, and data storage, retrieval, and display. Conversion of near-field measurement data to far-field radiation patterns is also automatically done. We also developed the software for controlling the robotic arm in the robotic arm antenna measurement system. These antenna measurement systems go up to 1.1 THz, only limited by the THz frequency extenders available in the lab.

We developed the software for computing the Mueller matrix and its polar decomposition and displaying the corresponding images for polarimetric imaging.

We designed THz probes and had them fabricated by a commercial vendor in France. We also equipped the probe with 3D printed absorber to eradicate the 1dB ripple in the measured radiation pattern.

We developed a printing process for dielectric lenses operating at 300 GHz. It outperformed the printing approach recommended by the manufacturer of the 3D printer (Formlabs). We were invited to display our lenses at the Shenzhen and Shanghai trade shows of the company.

6.8 Other education activities and/or training programmes developed:

We have co-organized/co-sponsored the following workshops and conferences (http://www.ee.cityu.edu.hk/skltmw/confernece.html):

- Workshop on Dual Robotic Arm Measurement Platform, 18 January 2023
- Workshop on High-Frequency Devices and Semiconductor Technology, 15 December 2022
- 2021 Cross Strait Radio Science and Wireless Technology Conference, 11-13 October 2021
- 2020 Asia-Pacific Microwave Conference (APMC 2020), 8-11 December 2020
- Joint SKLTMW-XLIM Workshop on Electronic Science, 6-7 December 2018
- COMSOL Multiphysics & Application, 21 November 2018
- The 18th IEEE (HK) AP/MTT Postgraduate Conference, 7 October 2017
- 10th Global Symposium on Millimeter-Waves (GSMM2017), 24-26 May 2017
- Workshop on Millimeter-Wave Antenna Technologies for 5G and Beyond, 30-31 March 2017

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

In Stage 2, Goal No. 1, Deliverable 1, CMOS radiator IC integrated with on-chip phased-locked loop for circularly-polarized radiation and Stage 3, Goal No. 1, Deliverable 1, Beam-steering CMOS phased-array radiator IC with circularly-polarized radiation, we did not designed an on-chip circularly-polarized (CP) antenna. Instead, off-chip antennas using 3D printed DDL antennas and metasurface antennas fabricated by micromachining were employed for the CP generation.

In Stage 2, Goal No. 1, Deliverable 2, Nano-antenna with 3D plasmonic contact electrodes combined with carbon photoconductors and Stage 3, Goal No. 1, Deliverable 2, 3D plasmonic plasmonic contact electrodes with carbon nanoconductors and GaAs nanowires, we prepared 3D carbon photoconductors but the process was not compatible with the PCA. Instead the 3D carbon-based polyimide was reported in J228 for the 3D microstructured FSS to enhance the resonant frequency at the THz range.

In Stage 3, Goal No. 4, Deliverable 7, cancer treatment response was not monitored with THz methods as we could not access specimen samples with cancer treatment. However, we were able to distinguish cancerous samples and non-cancerous samples through THz spectroscopy.

In Stage 4, Goal No. 1, Deliverable 2, our own designed THz emitter and detector were installed in the TD-TDS for testing. We did not integrate them with solid-state light sources as their power was too weak. As stated, our state-of-the-art THz radiator IC outputs more power than our commercially available equipment by 2 orders of magnitude. Please refer to Section 8.2 for the rationale for investing more effort in the frequency up-conversion approach using mature CMOS technologies.

In Stage 4, Goal No. 4, Deliverable 6, we attempted the structural changes and substrate-binding properties of proteins by THz spectroscopy but failed, probably due to insufficient THz power. We observed THz response of the complexes serving as the probes but not the reactions from the proteins. The laser source of our 20 THz TDS system broke down, and it took almost 6 months to have it fixed. In any case, it has insufficient power and sensitivity for accurate measurement.

In Stage 5, Goal No. 1: Deliverable 2, a compact system based on our state-of-the-art 675 GHz radiator IC was constructed. Fine details of the imaged sample were displayed without the need to perform any Mueller polarimetric imaging due to the output power of the chip being two orders of magnitude higher than the commercially available THz equipment we have.
Project Management

6.10 Please elaborate how the PC has played his/her role in coordinating and managing the project.

The PC discussed the resources they needed with team members and monitored their respective progress. As mentioned in Section 6.8, the PC has been assisted by the project manager and engineers from SKLMW. He was also assisted by two administrative staff. They work closely with the research students of different team members on the project and THz measurements. While the team needs to achieve the deliverables as agreed in the indicative timetable for staged monitoring and funding, the PC also encourages team members to broaden their research activities within the scope of THz research but not necessarily confined to the TRS projects. The PC also occasionally visited CityU members to discuss the project with them and encouraged them to request funding support.

7. Awards and Recognition

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

Please refer to 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?

Haifeng Zhou, Shangcheng Kong, Kam-Man Shum, Liang Gao, and Chi Hou Chan, "A 320 GHz fully integrated beamsteering IC," the *14th Global Symposium on Millimeter-Waves & Terahertz*, May 18-20, 2022, Yonsei University, Seoul, Korea (30-minute presentation)

L. Gao and C. H. Chan, "High-power terahertz source in CMOS," the 22nd edition of the *National Microwave Days* in Limoges, France, June 7-10, 2022. Keynote Speaker (45 minutes). The theme of the conference is "Imaging and Millimeter and Terahertz Telecommunications".

L. Gao and C. H. Chan, "Terahertz radiator array chips," *Workshop on IC Advances in China*, June 22-24, Shenzhen, China (online). Keynote Speaker (40 minutes). The other keynote speaker was Professor Ruonan Han of MIT. There were over 2000 registrations for the workshop, and over 800 people were online during my presentation. All conference speakers must have paper(s) published in the *IEEE Journal of Solid-State Circuits (JSSC)* or *IEEE Solid-State Circuits Conference (ISSCC)* within two years.

Chi Hou Chan, "THz research at State Key Laboratory of Millimeter Waves, Partner Laboratory in City University of Hong Kong," Keynote Speech, IEEE International Workshop on Electromagnetics 2017 (iWEM 2017): Applications and Student Innovation Competition, May 30th – June 1, 2017, University College London, London, UK.

C. H. Chan, "Terahertz Antennas – Design, Fabrication and Measurement" Keynote Speech, 2018 International Workshop on Antenna Technology (iWAT), March 5-7, Nanjing, China.

C. H. Chan, "Millimeter-wave & terahertz antennas for 5G and beyond," 2018 Hauwei Strategy and Technology Workshop (STW), May 15-17, 2018, Shenzhen, China (invited)

C. H. Chan, "THz antennas – design, fabrication and testing," 13th European Conference on Antennas and Propagation, EuCAP2019, Krakow, Poland, March 31-April 5, 2019. Article number 8739871. (40-minute invited paper)

Chi Hou Chan, "Terahertz Antennas for 6G and Beyond – Design, Prototyping, and Characterization," One-hour Keynote Speech, 2022 Fifth IEEE International Workshop on Mobile Terahertz Systems (IWMTS), 4-6 July 2022, Duisburg, Germany, hybrid workshop.

10th Global Symposium on Millimeter-Waves (GSMM2017), 24-26 May 2017, Chi Hou Chan, General Chair

2020 Asia-Pacific Microwave Conference (APMC 2020), 8-11 December 2020, Kwai-Man Luk, General Chair

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

N/A

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):

Award received by students

- Yang Chenfeng, First Prize, Antennas and Propagation Session, the 23st IEEE HK AP/MTTPostgraduate Conference, 2022, Nov. 19, 2022, Virtual Event, Hong Kong. He worked on 1THz Bessel beam frequency scanning
- Yan Boxun, Silver Award, ASM Technology Award 2022, June 30, 2022, Hong Kong. He worked on photoconductive antennas. The award carried HKD 30k cash award.
- Gao Liang, First Prize,Microwave Theory and Techniques Section, the 22 nd IEEE HK AP/MTT Postgraduate Conference, 2021, Nov. 20, Virtual Event, Hong Kong. He worked on THz radiator IC
- Kong Shangcheng, First Prize, Antennas and Propagation Session, the 21st IEEE HK AP/MTT Postgraduate Conference, 2020, Nov. 21, Shenzhen and Hong Kong. He worked on THz on-chip antenna

8. Impacts

8.1 What are the current and expected impacts of the project on the long-term development of Hong Kong (social or economic development, e.g. patent, technology transfer, collaboration with external organisations, etc.)?

Radiator ICs, beam manipulation, and imaging at THz frequencies are some of the key outputs of this TRS. One of the important features in the future 6G wireless communications, to be deployed in 2030, is the integration of sensing and communications. Our experience gained in this TRS well positions us to meet the challenges of future 6G and beyond with operating frequencies up to several hundreds of GHz. The following patents have been granted, and many more are pending.

Liang Gao and Chi Hou Chan, Two-Dimensional Scalable Radiator Array, US Patent No. 11,670,862 B1, 6 Jun 2023.
Chi Hou Chan, Gengbo Wu, and Ka Fai Chan, Leaky-Wave Antenna, US Patent No. 11,611,149 B2, 21 Mar 2023.
Chi Hou Chan, Hai Feng Zhou, Kam Man Shum, Oscillator Circuit, US Patent No. 11283405 B2, 22 Mar 2022.

The Central and HKSAR governments are keen to make Hong Kong a global innovation hub. We need an industry that opens to a worldwide market and can attract and retain talents with sustainable growth that will last for decades. Market Research Future, an international research company, reported in October 2022 that 6G market will reach USD 340 billion by the end of 2040, representing a compound annual growth rate of 58.1% from 2031 to 2040. In addition, many global information and communications technology (ICT) conglomerates have headquarters in the Greater Bay Area. An industry building around IC design for 6G would attract talent to Hong Kong. Against these backdrops, it is not difficult to see the long-term impact of the research outputs of this TRS in THz ICs for 6G in the socioeconomic development of Hong Kong and attracting talent.

The HKSAR government is about to roll out the Research, Academic and Industry Sectors One-Plus Scheme (RAISE+Scheme) in which HKD 10 billion will be used to fund at least 100 research teams from universities on a matching basis, to become successful start-ups. We are now actively reaching out to companies to seek matching support for the scheme. Our time and patents constitute part of the university matching.

8.2 Others (please specify):

Without the support of the TRS, we would not be able to kick-start our research endeavor on THz IC sources. Within six short years, we are now recognized as a forerunner in high-power THz sources using mature 65nm CMOS technologies. In the just approved GRF project, “CMOS Reconfigurable Terahertz Source and Detection Array for Fast High-Resolution Imaging/Sensing Applications,” funded at HKD1,276,987 with a rating of 5 (Chi Hou Chan, PI, Liang Gao and Gengbo Wu, Co-I), all five reviewers rated the PI’s track record in the field “Excellent”. Some encouraging comments are quoted verbatim as follows: (i) Strong research team with world leading standing; (ii) highly likely to lead to world first results; (iii) This project would enable the integration of THz imaging and sensing into 6G, contributing to developing a sustainable industry in Hong Kong; (iv) The proposed THz technology of integrating relatively high power source and detector arrays in a commercial CMOS process is highly original and innovative, especially given that the proposed objectives are built-on very recent (state-of-the-art) achievements by the PI, and not just copied from other research groups; (v) The PI has an outstanding track record and is a world leader in this field of terahertz circuits and integrated receiver arrays using mainstream silicon technology. The proposed research pushes the frequency of operation to new limits, going beyond the current state-of-art. The rapid introduction of 5G showed that mainstream silicon is the right approach for mass production, even if more esoteric technologies can give higher performance; (vi) Figure 6 compares the applicants' previous results with other work published in major international conferences and confirms that is is world leading; and (vii) It is worth emphasizing that the "terahertz" band is being approached from two directions by different groups of researchers: from above, using techniques such as ultra short pulse lasers and optical benches: and from below, using silicon IC technology. This proposal is very clearly taking the latter approach, which is far more relevant to the cited 6G communications, sensing and imaging systems. I mention this in case referees that use the optical bench approach are critical of the performance figures quoted. The proposed silicon IC solutions are not the highest performance for power and efficiency, but are probably the only realistic route to commercial exploitation in 6G. For completeness, note that there are niche two-terminal terahertz sources somewhere in between, but these are also unlikely to be adopted in 6G hardware.

Comment (vii) above echoes our strengthening of the effort in the frequency up-conversion approach in THz IC designs while lessening that in the down-conversion approach in photoconductive antennas during the TRS execution.

9. Sustainability of the Project

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

There are many new ideas that evolved from this project, leading to the new projects listed in 9.2. Metasurface technologies were developed in the TRS with only one THz source, as the frequency extenders cost HKD 2m per pair of transmitting and receiving modules. With the THz IC sources, we can develop new metasurface technologies with multiple sources to manipulate the radiation for specific coverage and extend the communication range. For radiator IC, THz on-chip antenna needs to be developed. We have developed miniature patch antennas to pack more radiating elements into a chip, as evident by the 144-element IC radiating 8mW at 675GHz (J275). We only intended to construct 2D images in the frequency domain for Mueller polarimetric imaging. We later developed a time-domain approach to construct 3D Mueller matrix images with the third temporal dimension. To conduct the polarimetric imaging, we need specially designed focus beam antennas. We developed a DDL approach realized by inexpensive 3D printers, as presented in Section 6.1. Our work on THz antennas led to new antenna research directions, especially that of antenna-in-package operating at THz frequencies. Beam manipulation was initially achieved using dispersion engineering or THz phased array. Active tuning of the meta elements of the metasurface can be achieved using phase change materials such as vanadium dioxide with proper voltage bias. This led to the investigation of other functional materials. Another important new idea is the briding of photonics and THz technologies in THz photonics, which will significantly impact future high-speed communications, especially for base-station applications.

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

- An Enabling Technology for 6G Wireless Communications, Collaborative Research Fund, Research Grants Council, Amount: HKD $8,339,652, 1 Jun 2023 - 31 May 2026, Chi Hou Chan (PC), Kaibin Huang (HKU, Co-PI), Pui-In Mak (U of Macau, Co-PI), Hang Wong (CityU, Co-PI), Can Li (HKU, Co-PI), Zhongrui Wang (HKU, Co-PI)
- On-Chip Antennas and Arrays for Future 6G, GRF, RGC, Amount: HKD $838,393, 1 Sep 2021 - 31 Aug 2024, Chi Hou Chan (PI)
- Enabling Technology for 3D Mueller Polarimetric Imaging at Terahertz Frequencies, GRF, RGC, Amount: HKD $845,055, 1 Jan 2021 - 31 Dec 2023, Chi Hou Chan (PI)
- 3D Printed Lens Antennas for a 3D Terahertz Imaging Platform, GRF, RGC, Amount: HKD $673,470, 1 Aug 2019 - 31 Jul 2022, Chi Hou Chan (PI)
- CMOS Reconfigurable Terahertz Source and Detection Array for Fast High-Resolution Imaging/Sensing Applications, RGF, RGC, Amount: HKD $1,276,987, 1 Jan 2024-31 Dec 2026, Chi Hou Chan (PI), Gao Liang (Co-I), Geng Bo Wu (Co-I)
- Investigation of Terahertz Antenna Designs for 6G Communications, GRF, RGC, Amount: HKD $838,393, 1 Jan 2022 – 31 Dec. 2024, Hang Wong (PI)
- Investigation of Wideband Antenna-In-Package Designs for 6G Communications, GRF, RGC, Amount: HKD $ 1,075,574, 1 Jan 2024-31 Dec 2026, Hang Wong (PI)
- Investigation of Integrated Sensing and Communication Antenna Designs for 6G, GRF, RGC, Amount: HKD $ 1,039,527, 1 Jan 2023 – 31 Dec 2025, Hang Wong (PI)
- High-resolution antenna measurement system with robotic arms for millimeter-wave frequencies, CRF Equipment Grant, RGC, 1 Mar 2020-28 Feb 2023, Amount: HKD $4,103,932, Hang Wong (PC)
- Research on 6G terahertz beam reconfigurable antenna based on phase change materials, NSFC, Amount RMB 640,000, 1 Jan 2021-31 Dec 2024, Hang Wong (PI)
- Integrated lithium niobate photonics for millimeter-wave applications, ECS, RGC, Amount: HKD $454,325, 31 Mar 2020-30 Apr 2023, Cheng Wang (PI)
- Efficient terahertz generation in nanophotonic lithium niobate waveguides, GRF, RGC, Amount: HKD $1,057,394, 1 Mar 2021- 29 Feb 2024, Cheng Wang (PI)
- An integrated millimeter-wave photonic phased array receiver system, GRF, RGC, Amount: HKD $1,075,574, 1 Jan 2023 – 31 Dec 2025, Cheng Wang (PI)
- Design of wideband high-gain multi-beam THz antennas based on modified Luneberg lens and

magneto-electric dipoles, GRF, RGC, Amount: HKD $ 1,228,619, 1 Jan 2024-31 Dec 2026, Kwai-Man Luk (PI)

- Advanced Antenna Technology for a Smart World, AOE, RGC, Amount Requested HKD $53,000,000, Kwai-Man Luk (CP), result pending (funded on July 13, 2023)

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

There are new collaborations developed from this project. A research assistant, Shaoxin Huang was recruited from Peking University to work on THz imaging. He was the PhD student of Professor Mingyao Xia, and we collaborated on the Mueller matrix imaging. Shaoxin Huang spent two years with us to work on his PhD thesis. He joined our team as a postdoctoral fellow upon receiving his PhD from Peking University. A research assistant, Dashuang Liao, a PhD student of Professor Haogang Wang of Zhejiang University, visited our team and worked on THz holographic imaging. Dr. Jun Yan Dai, a postdoc from Southeast University with Professor Tei Jun Cui's group spent two years as a postdoc with us and we collaborated on field manipulation based on space-time-coding.

Other new collaborations include the CRF project (An Enabling Technology for 6G Wireless Communications) with the University of Hong Kong and the University of Macau. The State Key Laboratories of Terahertz and Millimeter Waves (City University of Hong Kong) and Analog and Mixed-Signal VLSI (University of Macau) will work on the integration of terahertz circuits and the microwave/millimeter-wave circuits into a single chip. The AOE project led by Professor Kwai-Man Luk (PC) has five antenna design tracks on antenna innovation and one basic technique and technology team. Track 1 Smart Electromagnetic Surface led by Professor Ken Tong of UCL will advance his surface-wave work for signal broadcasting to programmable surface waves for directing the signal to specific locations. In Track 3 High-Gain Planar Antennas led by Professor Steve Gao of Chinese University of Hong Kong, novel leaky-wave antennas operating at D-band from 110 to 170 GHz will be developed for same frequency scanning. In the Basic Technique and Technology Team on Advanced Micro/Nano-Technologies for High-Performance Antennas led by Professor Stella Pang will undoubtedly be benefited from the experience in the fabrication of THz antennas using DRIE and 3D printing as reported in Section 6.1.

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 refer to 9.3.

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	275 Please refer to appendix I for details	85 Please refer to appendix II for details	N.A.	N.A.	N.A.	N.A.

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

12. The Layman's Summary

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

This project embarks on researching and developing a compact terahertz (THz) system for imaging and spectroscopy. Exiting equipment, both in frequency- and time-domain, are bulky in size and low in output power. Therefore, the image resolution and the thickness of the sample under test are restrictive. Furthermore, the adopted mechanical raster scanning approach limits the imaging speed. Our goals are to reduce the form factor of the THz system and enhance the imaging speed and quality. We first developed Mueller matrix polarimetric imaging to enhance image quality with our existing equipment. For the frequency-domain system, we developed a wide range of high-gain and focused beam THz antennas so that THz radiation can be concentrated to a designated location of the imaging target. Radiation with different polarizations is also produced for the polarimetry measurements. For the time-domain system, we developed photoconductive antennas with graphene and semiconductor nanowires incorporated with wideband THz polarizers for the time-domain Mueller matrix imaging. To reduce the form factor of the imaging system, we developed state-of-the-art high-power THz source integrated circuits (ICs). The tiny chip operating at 675 GHz (or 0.675 THz), occupying a chip size of 2mm×1.7mm area, is tunable from 643 to 689 GHz. The chip can generate 8.1mW, two orders of magnitude higher than our commercially available equipment, enhancing the image resolution without resorting to Mueller imaging. The chip also allows beam scanning from -45º to 45º, alleviating the slow speed of mechanical raster scanning. We have developed a new type of antenna whose fundamental radiation characteristics, including polarization, amplitude, frequency, direction, and phase, can be manipulated through software control only, paving the way for the integration of communications, imaging, and sensing. We have also developed an array of transition metal complexes as biological optical and THz spectroscopy probes.

The results achieved in the TRS led to many new projects, sustaining and strengthening our leadership in THz research.