Report of
The 4th RIKEN Center for Advanced Photonics Advisory Council
(RAPAC2023)

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Committee Members

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RAPAC 2023 Summary

[The RIKEN Spirit]

"RIKEN, Japan's premier scientific research institute, seeks to be a place where scientists conduct the research that they themselves wish to pursue, research that coincides with the creation of knowledge needed to secure humanity's future, a place where science and society converge and deepen mutual trust. For over a century, RIKEN researchers have faithfully handed down this tradition and made this RIKEN Spirit."

[RAP features]

At RAP, extremely broad-based photonics research has been developed in a multi-layered scheme, and includes cutting-edge research ranging from atomic and molecular physics to bioscience, microfabrication, laser processing, and other applications. The scheme of advanced photonics science supported by state-of-the-art technology is made possible by using internal circulation, and a system that allows researchers to see their own limits and goals to break through from the interaction has been realized. A virtuous cycle is created in which the strict demands of advanced scientific research lead technological development, while the new technologies that are achieved facilitate the achievement of scientific research goals.

A symbolic number for RAP is 10^{-18}; attosecond science by carrier envelope-controlled pulse, 10^{-18} accuracy in time, by optical lattice clock, 10^{-18} mol detection by Liquid-interface-assisted surface-enhanced Raman spectroscopy, 10^{-18} J TH detection by upcoversion technique and so on. Every researcher in this group feels the same atmosphere and collaborates with each other with high respect.

The relationship between science researchers and technical development is complex and dynamic, and they always stimulate each other. Not only pure scientific research, but also advanced technology development is still attractive research, and it has the ability to captivate researchers.

Before the 2nd World War, RIKEN pursued pure scientific research in this way, and established companies to return and disseminate the knowledge gained through research to society. After the war, RIKEN restricted research to basic research and stopped direct technology transfer through affiliated companies. In the sense of pursuing basic science, the Max Planck Institutes in Germany became a model. The value of technology transfer is also recognized now and RAP plays an important role for that.

At the opening session of RAPAC 2023, the RIKEN Spirit in Horizon 2030 was presented by the RIKEN Executive Council. It clearly indicates the path forward of RIKEN, and the Advanced Photonics Center RAP will make an effort to embody the 100-year history of RIKEN and the spirit of RIKEN in its next plan. We, the AC members, were deeply impressed by the above-mentioned explanation, and in light of such direction, we made efforts to understand the current research achievements and the orientation of the RAP teams.

[Mission of RAPAC 2023]

The RIKEN Center for Advanced Photonics (RAP) was started in 2013 and is in the 6th year of the second term program. The RAP Advisory Council evaluated the quality of the activity of RAP teams in 2019, and sent the RAPAC 2019 report to the executive council of RIKEN.

The tasks for RAPAC 2023 are as follows,

1. An external evaluation of the performance of each team leader was finished in RAPAC 2019.
2. Checking points: How the previous proposal to RIKEN was handled and reflected?
3. Evaluation points: Improvements and proposals for the next 10-year period.

4. Request points: What is the request to support for RAP by the RIKEN Headquarter for next 10 years proposal?

[Progresses of RAP]
The RAPAC 2019 summarized the report as follows: "RAP is making remarkable progress in the second term in many directions; world-leading research in basic science, development of fore-front technologies, and collaboration with domestic and international R&D activities at universities, government labs, industry and also RIKEN. They believed that these activities are well in line with the 4th Mid-to-long-term Plans of RIKEN (2018-2025)."

As mentioned, the group review reports the following, AC members reconfirmed the activity results of RAP and have the same impression as the 2019 report. RAP kept the same lines and created new directions during the past five years.

The Advisory Council (AC) is deeply impressed by the RAP team's achievements in remarkable advanced photonics research and their cooperative and coordinated efforts on mutual communications. RAP has succeeded in organizing active research teams which cover a wide range of photonics works from fundamental sciences to applied photonics, and their effort to adapt to the social requirements. This is crucial for the whole of RIKEN because advanced photonics is really the basics of various modern sciences in this century.

All comments on the research activities are quite positive. The discussion at the AC meeting was concentrated on the continuity and sustainability of research teams with high standard today. Recruit of high-quality human resources and expanding of financial support for the next ten years should be the key.

[Research Activity]
<Extreme Photonics Research Group>
We will briefly report our conclusions on the Extreme Photonics Research Group and go individually through the group. First is the attosecond program. With Drs. Midorikawa and Takahashi, we have seen absolute world-leading capability in the development of driver lasers and attosecond sources, particularly the three-color synthesizer leading to the capability to produce GW level isolated on attosecond laser pulses. That is a capability that exists here and that exists nowhere else. No matter what would be there trying to try and send to set something up like this is truly unique. And this is also reflected in an absolutely excellent publication record. Now these capabilities they create are truly unique opportunities in attosecond science. In that sense, we feel that the group could be world-leading if a few things were organized to use these sources to answer key questions in attosecond science. To make that possible, we feel that it's necessary to really widen the network of collaboration, including collaboration with theoreticians that are active in this field, or preferably to really bring in dedicated people. For example, a new principal investigator is pushing the application of attosecond science and attosecond pulses to attosecond science problems. Someone who is mainly driven by the desire to do research on attosecond science, based on the absolutely fantastic technological developments that have been done. Next we will describe the ultrafast spectroscopy team led by Dr. Tahara. There we saw a perfect balance between pushing state-of-the-art of technology, the time domain Raman spectroscopy, and very innovative research on tracking chemical reactions that liquids interface, and also very important applications of these unique techniques. The publication record is exemplary. We saw the work by Dr. Katori. Now none of us on the panel is especially some optical clocks, but we were impressed by absolutely with the world record-setting performance of these clocks and the way that this team is involved in strong international collaborations. This team is making very important efforts to transfer to the state-of-the-art of what can be done in the research laboratory out of the lab. The technology also becomes very relevant for societal applications. We thought this work was truly impressive. Then we saw the

work by Dr. Kato with the quantum optoelectronics. We believe excellent capabilities have been developed and so far applied to carbon nanotubes. It can pave the way for investigating other 2D materials with potential device applications. In this team, we also saw an excellent mentorship record, with three former group members having moved on to become professors. Finally, there was the work presented by Dr. Morimoto, the leader of the new Hakubi team, who is in the process of establishing a very exciting new research direction on ultrafast, even attosecond electron pulses from monitoring and controlling chemical and physical processes. It is a very impressive experiment that is coming together there. We are also very impressed by the fact that in the short time that he has been here he has already established a very important relationship with the top industry in the field. As far as we can tell, this work also has a bright future.

<Subwavelength Photonics Research Group>
We would like to make a specific comment on the bioimaging area first. The SCLIM-2 developed by Dr. Nakano is superior to other super resolution microscopes, in terms of temporal resolution. This microscopy has been exploited for comprehensive understanding of mechanisms of intracellular membrane traffic. The K version is planned for commercialization so that many microscopy technologies will be widely used. We also hope that the M version that pursues extremely high spatiotemporal resolution will be maintained at RAP and made available to leading researchers. Dr. Miyawaki has developed StayGold, a photostable GFP that has made many molecular biologists happy. In his presentation we saw mitochondria moving in real time for the first time. We have only seen time-lapse images before, so it was very impressive and hope that multicolor versions of StayGold will be developed. We were also impressed by the research result of imaging activity of cells in cerebellum, which showed that information processing is carried out in a time resolved manner like computer communications. Dr. Yokota has developed a new algorithm for image processing using machine learning. Over the past decades, AI technology in image analysis has become indispensable and this arch is growing in importance over the years. He’s not only familiar with software for image analysis and information theory, but also with experiments such as obtaining image data or CD internal structure by himself. He has collaborated with many companies and obtained many external research funds. Also, He has created a platform to analyze and utilize images. We hope that his image analysis platform will become a global standard in the process of performing TRIP, which President Gonokami is advocating.
Next, we will summarize feedback of two areas. One is the Innovative Photon Manipulation Research Team by Dr. Tanaka and another one is the Advanced Laser Processing Research Team by Dr. Sugioka. Overall, their research is innovative and some of their achievements are very visionary and revolutionary and they’ve published many papers in top journals. Their scientific discoveries and understanding have led to a number of technical breakthroughs. The first one is a study of two photons for 3D printing on metals by Dr. Tanaka and usually pretty mellow printing the mainstream projects for polymers and he has made it to metals which is a really great improvement, probably revolution. This is also work on field driven 3D printing, which has made the printing process apparel which is also very revolutionary. As for Dr. Sugioka, he has done work on liquid interface assisted surface enhanced Raman spectroscopy (LI-SERS) in three-dimensional microfluidics. It’s kind of a revolution because it achieved the enhancement factor by a factor of 1,000,000 compared to the conventional SERS. This is a new discovery and much more powerful than many other common approaches. The SERS substrate composed of just two-dimensional periodical structures generates such ultrahigh enhancement, which is not only the physically new but also defies common understanding. Additionally, it has great potential for surface modification and functionalization and their research works are very multidisciplinary. The technique they have developed is to integrate many aspects in multi-physics, multi-dimension and multi-scale will have a positive impact in biomedicine, microelectronics and sensing. They also developed very successful educational programs. Many of their postdocs and PhD students have become professors at top universities. Additionally, they're very internationally recognized and respected, which is evidenced by the number of invited talks given at international conferences. They also chair

international conferences and serve as honorary professors at international institutions. And then, Dr. Sugioka and Dr. Tanaka's groups are also very international, which means their research is more diverse and more and more creative. As for feedback on challenges and opportunities. We think their inventions are original, innovative, and have high value in the industrial future. The group can always reconsider industrialization offices to have more like interactions with industry. Japan is traditionally very strong in precision engineering and their efforts will further strengthen the position of competitiveness in this area for Japan. Japan's research programs need long-term stability and continuity which will require budget and personnel support. Their strength is rooted in their robust infrastructure and the accumulation of long-term expertise. Therefore, we believe that they should eliminate any potential gaps that could hinder our future capabilities. To achieve this, they need to proactively plan and communicate that they are committed to pioneering future endeavors. This approach will help them attract a greater number of young, talented individuals to their programs.

<Terahertz-wave Research Group>

The Terahertz Group is performing highly visible efforts internationally in various aspects of terahertz research. They have made great contributions and they continue to break records, world records in many aspects, which is reflected in high quality publications. It comes from the group. In particular, in the presentations, we heard that Dr. Minamide's team effort on backward terahertz wave parametric oscillators provides world record power within a compact as an oscillator configuration that is comparable to classrooms that are large facilities. That's a very impressive effort that, with the commercialization opportunities it brings a lot of new opportunities through the terahertz field for practical applications. In the same line, the terahertz detection techniques that they are using based on optical parametric conversion are very impressive in that they push the limits of detection sensitivities to the quantum limit and provide a very large dynamic range. This opens up a lot of possibilities for imaging and sensing in industrial environments. Dr. Hirayama's team's efforts on quantum cascade lasers are at the forefront of the field. Very novel work on looking at new schemes for making these terahertz emitters based on three-level, carrier excitation novel materials such as gallium nitride and to push the limits of operation to room temperature operation, surface emitting lasers for high powers are very impressive and again at the forefront of the field. Dr. Otani's team's efforts on superconducting kinetic inductance detectors with super-high sensitivity at the quantum limit and their application to space are again breaking sensitivity records. And the very diverse range of applications that the team is exploring in collaboration with many groups, from biology to states to security imaging, is of great interest to bring the terahertz field into more practical settings.

The research activities of the Terahertz group are at quite a high level. If something could be added, we recommend that they consider new directions of research field and to recruit young PIs. The terahertz research field is now growing rapidly and spreading across the world. In particular, semiconductor technology for 6G telecommunication is quite important and also quantum spectroscopy and quantum sensing are emerging as one of the most important subjects in physics and chemistry. All activities in the terahertz research group have already included the very initial stages of this quantum terahertz research. Please think more about such new directions in the future. If the budget allows, we also recommend the director of RAP and also the president of RIKEN to hire new PIs for this group to expand the activities, especially terahertz quantum research or terahertz semiconductor device research. Finally, we also commented on the long-term activity of developing organic nonlinear crystal growth in Minamide's team. It is quite important to keep the technique for future sensitive nonlinear process in quantum detection. We recommend to keep the technology in the future.

<Advanced Photonics Technology Development Group>

We have summarized the recommendation and evaluation results for the Advanced Photonics Technology Development Group. Within the group, we evaluated the current activities as outstanding. The AC recommendation made at the previous meeting was that research targets must be well controlled from the viewpoint of scientific and social requirements, as well as from the personnel of each group. The teams have so far embraced the suggestion very well. Especially the Neutron Beam Technology Team has nearly realized a practical system for on-site usage. The research activities of the group focused on practical applications can be evaluated as satisfactory, including Dr. Wada and Dr. Yamagata's teams. As for the machine shop, which is a very important facility to enhance the performance of RIKEN centers, sustainability has been greatly improved, such as the acquisition of one or two positions for engineering staff and funding for machine replacements. We recommend seeking continuous support from RIKEN headquarters. Finally, as a suggestion to enhance the presence of the machine shop, it would be better to prioritize the research and development of an original novel fabrication method as a research target in this group. These are my personal recommendations. For the most part, we do not find any significant problems in this group.

[Human resource]

Human resource problems are divided into two parts: First is the retirement of powerful PIs in the near future and the other is the recruitment of young post doctorate fellows.

[PI issue]

In the next ten years, several powerful PIs will reach retirement age. It is not easy to find a new and powerful PI immediately. How to continue the current high-level research depends on the policies and philosophy of RAP and RIKEN.

Foreign committee members asked why there are no foreigners and only a female among the research leaders, PIs. RAC has to create new ideas to attract foreign PIs and female PIs in the near future.

(see ref. 1)

[PD mobility and carrier pass]

We found problems with PD researchers in RAP.

a) 10 years PD work is too long. AC members agree with the following advice.

"At present, postdoctoral researchers at RAP spent up to a decade within the organization. This is a very long time, especially if no possibilities for continued employment within RIKEN exist. Employment of postdoctoral fellows beyond a period of 4 years should be accompanied by active mentoring on career possibilities, exploring to what extent the postdocs can be groomed for successive leadership positions within RIKEN, or mentoring them towards a successful career outside the organization."

b) Human resource mobility.

As mentioned above, we recommend that PDs are mentored towards a successful career outside the organization. Bilateral human resource mobility is the typical characteristic of world-class research institutes. Junior researchers might use RIKEN as a jumping board to make their next career. When the other PDs who see it apply to follow in their footsteps, the mobility of recruit and career-making goes up. We should keep in mind that young researchers leaving RIKEN are also a direct contribution of their academic achievements to society, and that they will have a long-lasting impact.

(See ref. 2)

[Organization]

The structure of RAP is quite unique; big variation and mixing from fundamental physics, chemistry, biology, life science, wide range of wavelength x-ray to THz, ultrafast physics and ultrahigh precision optics, technological development for pure science and social requirements. RAP consists of a wide variety of teams corresponding to these fields, and every PI conducts research with a high degree of independence. Staff numbers for each team are small from the view of world standards. It is amazing that such small teams can produce excellent achievements.

[Theory support]

One of the problems of RAP structure is the lack of a theoretical team. The attosecond science team developed world-top-level attosecond drivers. Theoretical expectation before experimenting is important to investigate novel face of attosecond response and beyond. Theoretical support, preferably via the availability of in-house theory, will be vital. At this moment, the connection to theory depends on the PI's personal human network. We respect these PI's efforts and recommend a RAP supporting network the theoretical group world-wide. We believe RAP is quite attractive for the proactive theoreticians in the field of photonics.

[Foreign researchers]

Since the beginning of the Ukrainian war, millions of Russians have escaped Russia. Large numbers of excellent scientists and junior researchers moved away from Russia. This is a historical event. The first event was the Russian revolution and the second was the Jewish escape from Germany and Russia during the 2nd World War. The United States of America accepted these people and gave them academic positions. The U.S.'s dramatic growth in science and technology was demonstrated there. At that time Japan had no way to accept people. What is possible for today's Japan?

RIKEN is a leading institute in Japan. RIKEN developed the International Frontier Research System in 1986. It was quite a new scheme for pioneering works based on an international standard. The idea broke through the traditional framework of university-style research. Today, RIKEN should create such an innovative idea of the RIKEN structure as a whole.

[External fund]

In the RAPAC 2019 report we mentioned that the dependence on external funds should be decreased. RAP is preparing the mid-and-long term program for the next ten years. Many external funds expect relatively short-term results and goals. Such type of research is different from the next mid-and-long term program of RAP. RAPAC 2023 recommends the RIKEN board to raise the financial support to RAP and keep the RAP condition stable and sustainable.

[Supporting staff, interpreter]

How to distribute the deep knowledge obtained from leading research? It is not so easy. We need active science interpreters who can transfer deep knowledge from advanced work to outside society. We have no staff to support researchers in this field. We need especially talented staff to distribute the results.

Reference

ref. 1　理研 RAP の人員構成

Midorikawa team:	8 staffs, 4 PD, 3 foreign scientists, 2 students
Tahara team:	4 staffs, 0 PD, 1 foreign scientist, 0 student
Katori team:	2 staffs, 0 PD, 0 student
Kato team:	1 staff, 0 PD, 0 student
Takahashi team:	2 staffs, 1 PD, 2 foreign scientists, 1 student
Morimoto team:	0 staff, 2 PD, 1 foreign scientist, 0 student
Nakano team:	6 staffs, 0 PD, 0 student
Miyawaki team:	1 staff, 0 PD, 0 student
Yokota team:	7 staffs, 0 PD, 17 students
Tanaka team:	1 staff, 3 PD, 3 foreign scientists, 1 student
Sugioka team:	2 staffs, 2 PD, 2 foreign scientists, 3 students
Minamide team:	3 staffs, 1 PD, 3 foreign scientists, 0 student
Otani team:	2 staffs, 2 PD, 1 foreign scientist, 16 students
Hirayama team:	2 staffs, 0 PD, 1 foreign scientist, 2 students
Wada team:	12 staffs. 0 PD, 13 students
Yamagata team:	7 staffs, 1 PD, 2 students
Otake team:	7 staffs, 1 PD, 0 student

PI 17, staff 41+26 (26 は D の共有サポート部) PI:staff=1:2+α 平均
PD 17, foreign scientists 17
学生 49, 非常に偏っている。Yokota 17, Otani 16, Wada 13, Yamagata 2, Midorikawa 2, Takahashi 1, Sugioka 3, Hirayama 2

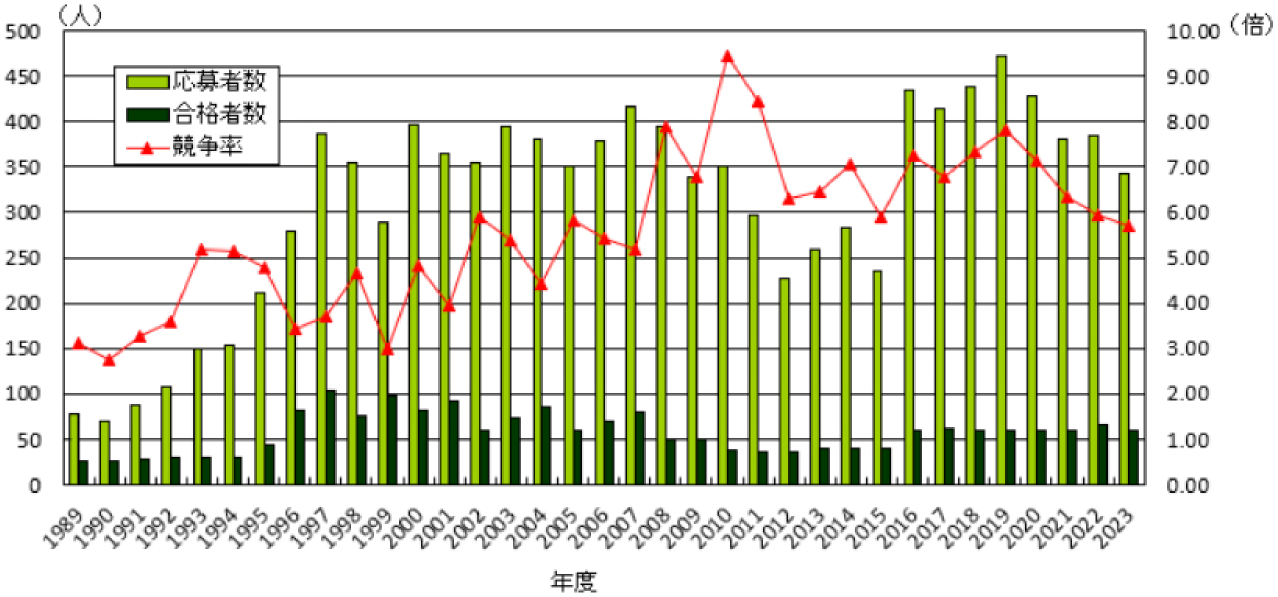
ref.3　PD history in RIKEN

RIKEN was the first research institute in Japan to introduce PD system named as Special Postdoctoral Researchers Program in 1989. This system works very well. RIKEN collects 110 to 120 Pds every year under high competition rate. It means RIKEN has a long history and rich experience on human resource mobility. The PD condition in the universities in Japan is poor in comparison to RIKEN. Salary level is 2.44 times higher and laboratory condition is better. In this sense, RIKEN should develop a new channel of human resource mobility for the high-end PD researchers in Japan. What is the next step for RIKEN Pds? University laboratories, or world-famous laboratories in abroad? RAP PIs have a big potential to introduce them to the world. Communication with human mobility is the essential function of world-class research institute.

(see ref.3)

ref.3　RIKEN PD history

基礎科学特別研究員制度への応募数・採用数・競争率推移



Appendix

[Extreme Photonic Research Group]
The Extreme Photonics Program consists of 6 teams, namely the teams of Drs. Midorikawa and Takahashi (Attosecond Science and X-ray photonics), Dr. Tahara (Ultrafast Spectroscopy), Dr. Katori (Space-Time Engineering), Dr. Kato (Quantum Optoelectronics) and Dr. Morimoto (Ultrashort Electron Beams). All teams very successfully give meaning to what the RAPAC sees as a central task of the RAP, namely, to strive for unique experimental capabilities and to pursue important scientific challenges.

Drs. Midorikawa and Takahashi run a world-leading activity on (a) the development of driver lasers for attosecond science and (b) the development of attosecond sources themselves. The two have been combined in the development of a unique 50 mJ, 3-color optical waveform synthesizer that permits the production of GW-level isolated attosecond laser pulses in the extreme ultraviolet (XUV) wavelength range, paving the way to attosecond pump-attosecond probe spectroscopy experiments. First steps towards this goal have already been realized in attosecond nonlinear Fourier spectroscopy (ANFS) experiments. Moreover, they have developed a soft X-ray high harmonic source using a 100 mJ mid-infrared (MIR) driver laser that permits single shot measurements in the water window. These results, reported in a series of high-profile publications, create unsurpassed possibilities to answer some of the key questions in attosecond science related to charge migration in molecules and charge dynamics in solids, and make it possible for RIKEN to be the world-leading laboratory in attosecond science. In order to achieve this, however, it is important to significantly widen the network of collaborations and/or to bring new scientists into RAPAC for this purpose e.g., a principal investigator pushing the application of attosecond pulses in pump-probe spectroscopy. Relatedly, theoretical support, preferably via the availability of in-house theory, will be vital. N.B. One of the proposed applications of the developed XUV sources is in the area of EUV lithography. The RAPAC recommends careful consideration of these ideas, given the fact that the only company that builds EUV lithography machines (ASML) has very strong existing connections with academic partners on this topic, first and foremost at the ARCNL research institute in Amsterdam, the Netherlands, which was co-founded by the company.

Dr. Tahara's ultrafast spectroscopy team displays a perfect balance between pushing the state-of-the-art of time-domain impulsive stimulated Raman spectroscopy (TR-ISRS) and important applications such as innovative research on tracking chemical reactions at liquid interfaces. By measuring Raman spectra in a time-resolved manner, TR-ISRS provides a very insightful combination of time-domain and frequency-domain information. The technique was applied to, among other things, the time-resolved observation of plasmon-driven dynamics of adsorbates on metal nano-particle assemblies. Future work includes the more widespread use of ultrashort (<10 fs) deep-UV excitation pulses. Another significant accomplishment by the group is the development of UV-excited time-resolved heterodyne-detected vibrational sum-frequency generation (UV-TR-HD-VSFG). Using this technique, it was observed that photochemical reactions of phenol at the air/water interface occur 10000 times faster than in the bulk. The publication record of the group is exemplary.

Dr. Katori has achieved world-record setting performance with the optical lattice clocks that he has developed. However, the scientific accomplishments of his team are perhaps even surpassed by their impressive track record of transferring state-of-the-art research capabilities out of the pristine environment of a sophisticated research lab into industry and into real-world applications, important examples being their demonstration of the operation of an optical lattice clock at the TOKYO SKYTREE (to test the gravitational redshift) and the application of their optical lattice clocks in geodesy measurements. To facility these applications, the group actively pursues size reduction of the optical lattice clocks, in collaboration with numerous industrial partners. The group is also very well connected internationally. Future work includes the development of “Longitudinal Ramsey Spectroscopy” as a means towards more favorable scaling of clock stability with measurement time.

Dr. Kato performs detailed research in the field of quantum optoelectronics, and has excellent research capabilities that have so far been applied to microspectroscopy measurements on carbon nanotubes. As such, the team is technologically in a position where significant impact can be achieved by using the available infrastructure for the investigation of 2D materials with potential for device applications. The group leader has an excellent record of mentorship, with several former team members already having been promoted to professorships.

Dr. Morimoto is the leader of Hakubi group and has established a very exciting new research direction on the use of ultrafast electron pulses for monitoring and controlling chemical and physical processes, aiming towards combining attosecond temporal and Angström spatial resolution. A very intriguing proposal is the proposed concept to control electron-matter interactions (e.g., electron-impact excitation of atoms and molecules) using temporally shaped electron pulses. Besides starting this research activity, it is very impressive that in his limited time at RIKEN he has already established a collaborative relationship with a leading industrial partner in the field.

General recommendation
The recruitment of junior researchers at the graduate and postdoctoral level is an important challenge in many research institutions around the world, and RAP is no exception. To sustain the development of the program in the years to come, it is important that talented junior PIs are recruited, who can follow in the footsteps of some of the senior PIs who are going to retire in the coming years. In doing so, it is important to exploit all available potentials, including in particular the recruitment of talented scientists from abroad and the recruitment of talented female researchers. At present, postdoctoral researchers at RAP spent up to a decade within the organization. This is a very long time, especially if no possibilities for continued employment within RIKEN exist. Employment of postdoctoral fellows beyond a period of 4 years should be accompanied by active mentoring on career possibilities, exploring to what extent the postdocs can be groomed for a successive leadership position within RIKEN, or mentoring them towards a successful career outside the organization.

[Subwavelength Photonics Research Group]
This team pursues exploitation of optics and photonics in the field beyond the diffraction limit of light.

B-1 Live Cell Super-Resolution Imaging Research Team

(1) Focus of research
Development of cutting-edge super-resolution optical microscopy for live cell imaging to understand the molecular mechanisms of protein sorting and transport in membrane traffic.

(2) Major achievements
1. Further development of the state-of-the-art SCLIM2 microscopy. It achieves 3-color observation with 3D spatial resolution of 70-100 nm and temporal resolution of 20 volumes/s.
2. This microscopy revealed the molecular mechanisms of membrane traffic as follows. First, it revealed that protein sorting and transport are regulated by the length of lipid ceramides in the endoplasmic reticulum membrane. Second, it was shown that cargo proteins transported to different destinations, the plasma membrane and the vacuole, are sorted through "zones" that are clearly compartmentalized on a single trans-Golgi network.

(3) Evaluation

1. SCLIM2 is the best super-resolution microscopy in terms of temporal resolution. It is a powerful tool for elucidating molecular dynamics occurring in living cells and has an extremely wide range of applications.
2. We recommended at RAPAC2019 that SCLIMS2 be used as a platform for bio-imaging at RIKEN and other organizations. Two types of SCLIM2, SCLIM2K and SCLIM2M have been developed. SCLIM2K is a prospective commercial model and SCLIM2M is a model that pursues extremely high spatiotemporal resolution with single photon counting.

(4) Recommendation
We recommend that SCLIM2K be commercialized, and that this microscopy technology be widely used. We also recommend that SCLIM2M be managed and operated at RAP before Dr. Nakano retires so that top researchers can continue to use it. SCLIM2M is an advanced microscopy system and requires personnel who can operate it.

B-2 Biotechnological Optics Research Team

(1) Focus of research
Development of bio-imaging technologies that capture spatiotemporal patterns of biological activities, mainly using fluorescent and bioluminescent proteins.

(2) Major achievements
1. The activity of the entire dorsal surface of cerebellum was successfully measured using a fluorescent calcium sensor protein. It was revealed that sensory information is processed in a distributed manner throughout the cerebellum.
2. StayGold, a bright and extremely photostable fluorescent protein, was developed. It enabled faster and longer quantitative analysis of microstructural dynamics of cell organelles. In addition, a fusion protein of StayGold and VHH antibody was used to reveal the detailed distribution of SARS-CoV-2 spike proteins in infected cells.

(3) Evaluation
1. The achievement of proving that the cerebellum performs distributed collective encoding, rather than parallel processing by local modules as previously thought, is groundbreaking. This will greatly contribute to the treatment of cerebellar diseases and the development of brain-based computers.
2. We recommended at RAPAC2019 the continued development of new fluorescent proteins that will be useful tools for life sciences. Because of its brightness and photostability, StayGold dramatically expands the spatiotemporal range of fluorescence observation and contribute greatly to quantitative studies in the life sciences.

(4) Recommendation
We look forward to the continued development of new fluorescent proteins, including monomeric and multicolor versions of StayGold, that will be useful tools for the life sciences.
Major research accomplishments have been achieved by senior researchers. We look forward to actively adding young researchers, post-doctoral fellows, and students to the team to foster the next generation of researchers.

B-3 Image Processing Research Team

(1)
Focus of research
Development of new imaging technologies and image processing techniques, and their application to science and engineering.

(2) Major achievements
1. Several fast and accurate scale-aware image filters have been developed that remove image structures smaller than a specific scale while preserving salient edges. Fast and high-quality results, which were difficult to obtain with conventional filters, were realized.
2. A framework combined with 3D imaging (3D-ISM), image processing (VCAT5), and cloud-based image platform has been developed. The three-dimensional microstructure of materials was analyzed at high resolution.
3. New deep machine learning frameworks have been developed that mimics the diagnostic processes of physicians. Using this technique, glaucoma was diagnosed with a high degree of accuracy.

(3) Evaluation
1. Fast and accurate scale-aware image filters preserve salient edges and converge to the target scales without artifacts.
2. The team is collaborating with various RIKEN centers, universities and companies, and the image communication platform has been adopted by several huge research projects in Japan. The platform will automatically collect images from microscopes in all RIKEN and this system will contribute to TRIP.
3. The team has successfully used machine learning to diagnose idiopathic pulmonary fibrosis, early-stage gastric cancer, and glaucoma. The contribution of this technology to the medical field is extremely high.

(4) Recommendation
The team aims that the image communication platform developed by the team will become the de facto standard of image-based science and engineering in Japan. We hope that the team will promote collaborative research with other countries so that the platform will become a global standard.

B-4 Innovative Photon Manipulation (Dr. Tanaka)
B-5 Advanced Laser Processing (Dr. Sugioka)

Achievements
1. Both research groups have been conducting cutting-edge research in the areas of micro/nanoscale material processing, fabrication, and characterization based on innovative photon manipulation and advanced laser processing. The scientific discovery and basic technologies established by these efforts are essential to support Japan’s initiative in regaining leadership and dominance in hi-tech industries such as microelectronics.
2. The research works are innovative, visionary, and revolutionary which are evidenced by many publications published in top journals.
3. Their scientific discoveries have led to a number of technical breakthroughs which are recognized internationally:
a. Two-photon excitation for nanoscale 3D printing of metals (Dr. Tanaka). This breakthrough made it possible to print metallic nanostructures while the conventional two-photon polymerization can only print polymeric nanostructures which are lacking multifunctional properties for various applications.
b. Field-driven 3D parallel printing (Dr. Tanaka). This ground-breaking work has successfully addressed a fundamental constraint in nanomanufacturing that spatial resolution and throughput cannot be gained at the same time. This approach allows the fabrication of multiple 3D nanostructures in parallel which can be scalable to large dimensions. The field-driven approach can also be used to tune the deposition process for different requirements in real applications.
c. Liquid-interface-assisted surface-enhanced Raman spectroscopy (LI-SERS) in 3D microfluidic

structures (Dr. Sugioka). LI-SERS strategically combines the advantages of SERS and microfluidics for highly sensitive spectroscopy of liquids. The unique combination of the microscale structures and nanoscale morphology in the microfluids enabled the record-breaking signal enhancement. The attomolar sensitivity of the LI-SERS is a promising innovation for biophotonics such as early screening of cancers.
d. Two-dimensional laser-induced surface structures 2D-LIPPS (Dr. Sugioka). 2D-LIPPS has been a target for research over decades. It has been a very challenging field with many puzzling phenomena unsolved so far. It is impressive that Dr. Sugioka's team had the courage and strategy to work on this topic. With the help of GHz burst mode of ultrafast lasers (another area in which this team has made significant contributions), the mechanisms of the 2D-LIPPS formation have been discovered. The understanding has successfully been applied to control 2D-LIPPS formation, which is a significant step forward from the current state-of-the-art approaches which can only produce 1D-LIPPS.
4. Research works conducted by both groups are multidisciplinary, tackling challenging multiphysical, multidimensional, and multiscale issues which cannot be effectively addressed in single disciplines.
5. Their research achievements have potential impacts on different fields, such as biomedicine, microelectronics, and sensing.
6. The research teams have successful educational and mentoring programs: which have provided an ideal venue for training and mentoring junior and senior researchers. Their efforts and contributions are evidenced by the number of postdocs they mentored. Many of the postdocs who carried out research in the teams have become faculty at top universities. The quality and number of PhD/Msc students trained in the teams are also outstanding as compared to similar research labs internationally.
7. The unit leaders and senior researchers are internationally recognized and respected. Their research activities are consistently ahead of the game in the fields. Their contribution in science and education have made significant impacts inside and outside of Japan.
8. The research teams are very international. They have many group members coming from different counties. They have also strong collaboration and frequent interactions with leading research groups internationally, have presented large numbers of plenary and invited talks in international conferences. They have also been recognized with honorary professorships in foreign universities. In addition, they have created, organized, and chaired top international conferences which have promoted research fields and connected young Japanese researchers to international research communities.

Challenges and opportunities
1. Their research outputs are strategically important for technological and economic development. It is suggested to work with RIKEN's Industrial Relation Office to find industrial partners who will benefit from the technical breakthroughs.
2. Japan has traditionally been strong in precision engineering; their efforts will further strengthen the competitiveness of the areas and provide technical foundation and support to create new business opportunities.
3. The research capabilities and core competence established by the teams are unique and hard to copy for others. It is important to maintain long-term stability and continuity with budgetary and personnel support. Once lost, these capabilities are hard to restore. They require top brains, infrastructures, technological windows, and long-time accumulation of know-how.
4. It requires early and long-term planning to keep core competence. It is important to make it clear that these groups will continue to be supported for a long time, so that young talent can be attracted to these groups.

[Terahertz Research Group]
The Terahertz Research Group at RIKEN has continued running a highly visible and internationally

respected operation over this review period. They have achieved world records in terahertz power levels and detection sensitivities and demonstrated a wide range of applications, which have been published in high-impact journals in the field.

Specifically, the work of Dr. Minamide's group on backward parametric oscillators, offering record-high terahertz power is both novel and unmatched in performance. It is fascinating that his group achieves very high terahertz power levels comparable with those from klystrons, through a compact and portable device, which could find many scientific and industrial applications. In addition, his work of ultra-sensitive terahertz detectors achieving quantum-level sensitivities through optical parametric amplification is very impressive and a great enabler for various imaging and sensing applications, as already demonstrated by his group. Furthermore, Dr. Otani's work on superconducting KID detectors, offering focal-plane arrays with quantum-level sensitivity is very remarkable. It is great that his group is planning to use these detector arrays for measuring cosmic background radiation, an application that required the utmost sensitivity provided by Dr. Otani's superconducting detectors. Apart from astrophysics applications, it is great that Dr. Otani's group is exploring a wide range of imaging and spectroscopy applications ranging from biology to security and agriculture. While these efforts on applications of terahertz systems show the breadth and depth of RIKEN's team, it would be helpful if they could hire more scientists and PIs to assist them with such an extensive research operation. Furthermore, the work of Dr. Hirayama's group on development of terahertz quantum cascade lasers (QCLs) is very impressive. Their research on the 3-level carrier excitation scheme and GaN quantum wells for increasing the operation temperature of QCLs and surface emitting QCLs for increasing the terahertz radiation powers are all very high quality and at the forefront of the field.
For the future direction of the terahertz research group, we have two recommendations: One is to add a new research field related to THz quantum sensing or semiconductor devise applications. The other is to be augmented by hiring a young PI in the THz field. The terahertz research field has been rapidly growing and expanded to include various boundary areas. In particular, semiconductor technology using CMOS or tunneling structure becomes important for next-generation telecommunications. It is important to emphasize that terahertz quantum optics and sensing is emerging as an important analytical method for quantum matter and as an important tool for quantum manipulation. The Terahertz Group has already begun preliminary research in these directions and should expand its direction more clearly in the near future. We also recommend to the Director of RAP and the President of RIKEN that young PIs be hired in the Terahertz Group in order to strengthen research activities. Considering the age distribution of PIs, it would be better to add young PIs who may be exposed to the new research areas mentioned above.

[Advanced Photonics Technology Development Group]
The group aims to utilize photon and neutron beams to realize cutting-edge photonic technologies that meet the demands not only of the scientific side but also of societal issues. Research and development are carried out with a strong viewpoint to practical application. This photonic technology group serves as significant technical support to APC and other fields of RIKEN sciences. This group works as a kind of bridge lab inside RIKEN and they open the window between fundamental research works and social requirements.

D-1 Photonic Control Technology Team

(1) Focus of Research
Dr. Wada's team works on the development of advanced solid state laser systems for various scientific research. His team aims to respond to the latest demands of laser science and technology and to contribute to human society through the application of photon beam technologies. This team plays an important role in strengthening the fundamentals of RAP.

(2) Major Achievements
1. In the MID-IR region, where no effective laser has been realized, a high output power of 100 μJ has been achieved while wavelength tuning the Cr: II-VI laser by intracavity DFG. This achievement has been effectively applied to detect polluting gases in the environment and is being considered for application as a gas monitoring technology in the next generation of agriculture.
2. This team developed a Lyman-α laser for muon microscope project in cooperate with other national institute groups including KEK, J-Park and universities. They tried to develop new laser material in order to adjust the laser wavelength to Lyman-α generation. It was a key device for this project. The technical potential of this team is so important for the laser application scientific community.
3. In response to the outbreak of COVID-19, which was a crisis for humanity, a tracer-free dust monitoring technology was developed based on the original LIDAR technology. In addition, UV light irradiation technology in a wavelength range shorter than 230 nm was proposed as a virus inactivation technology. In this process, the harm to the human body was studied in detail, and it was shown that there was no penetration into the inside of the epidermis. This result has been adopted as a criterion for governmental policy decisions.
4. The team is working on the use of laser technology to remove space debris that would hinder space exploration. Significant basic data has been accumulated regarding controlling debris trajectories by laser ablation.

(3) Evaluation
Active collaboration, not only within RAP but also with external research organizations, works quite effectively. Employment by external funds is promoted aggressively but well controlled, which strongly contributes to enhancing research and development qualities. The role of the D1 team is well-ordered regarding the selection of research topics, and the organizational management of PI works admirably and effectively.

Wavelength-tunable lasers in the MID-IR region are excellent. A novel gas monitoring system has already been realized by applying this laser, which helps solve environmental and agricultural problems. This can be said to be a significant example of the contribution of photonic technology to solving societal issues. To control COVID-19 infection, a severe societal problem, usable photonic technologies to inactivate the virus and monitor cough droplets that cause viral spread has been intentionally realized. Although COVID-19 has almost been conquered, a viral crisis is unavoidable for humankind in the future, and these are useful achievements for possible crises in the future. This team's output covers a wide range of exceptionally outstanding areas, from basic science to social applications.

(4) Recommendation
This team is highly active in promoting research and development, and it is important to maintain this status. In addition, collaboration and information exchange within the D Group have worked effectively so far, but there is potential to create even better original technologies through deep collaboration with optical fabrication researchers, as will be mentioned in the recommendation to D3 and D4 teams; novel photonic technologies in conjunction with the development of new and original fabrication technologies could lead to the creation of high-impact and highly sophisticated photonic devices.

D2 Neutron Beam Technology Team

(1) Focus of Research
Dr. Otake's team is promoting development of a RIKEN original compact neutron system, RANS, for specific applications in the non-destructive evaluation of bridges, roads, and other social infrastructures.

(2) Major Achievements

1. The Transportable RANS III, a further miniaturized version of the RANS III based on a proton accelerator, has been successfully developed. Excellent practicality that enables measurement times of several 100 mm square areas within a few minutes has already been established. RANS III is now in the stage of radiation safety tests, after which it is planned to start field operations.
2. They succeeded in analyzing moisture content in anchorages using RANS II.
3. RANSμ has been successfully developed using radioactive elements as a neutron source and has already been established as a method for assessing salt density in reinforced concrete structures.

(3) Evaluation

Research has progressed extremely well since the last RAPAC. In particular, the fact that development has reached a practical level is highly commendable. The benefits of non-destructive inspection of social infrastructures such as bridges and roads after a long period are highly significant.

(4) Recommendation

The construction of a test platform is necessary to confirm the safety of RANS III against radiation leakage, and this should be carried out as soon as possible to enable the field operation of RANS III. Research needs to be conducted from a comprehensive perspective. The leadership of the PI is excellent to have the participation of researchers from civil engineering and other fields. This viewpoint needs to be further strengthened toward the research stage for practical applications of RANS III. PI's age is increasing, although not only in this team. The status is approaching a critical period toward societal implementation. Both continued support and developmental reinforcement are crucial.

D3, 4 Ultrahigh Precision Optics team and Advanced Manufacturing Support team

(1) Focus of Research

Dr. Yamagata's team aims to meet academic and social demands in the optics and photonics fields by researching, developing, and realizing novel optical systems based on their outstanding processing technologies.

(2) Major Achievements

1. The team has realized complex and high-precision scientific systems for neutron optics and astronomical observation optics. It has collaborated with J-PARC, NAOJ, and the University of Tokyo to implement them concretely into cutting-edge scientific facilities. This team is executing its mission at a sophisticated level.
2. The team has independently developed various neutron interferometers. In particular, the super-mirror-based interferometer has a huge energy bandwidth, which shortens the measurement time and provides spectroscopic information. The required parallelism of the opposing multilayer reflectors is extremely challenging, and this has been achieved the world's first outstanding achievement.
3. The machine shop responds to requests from RAP but also from RIKEN in general and from non-RIKEN research institutes. The machine shop has highly skilled staff members, installed new processing systems such as a 5-axis machine and a CO_2 laser cutter, and maintained high-level competence. This was confirmed during the visit.

(3) Evaluation

This team is promoting the development of high-precision optical elements and instruments in response to the demands of both academia and society. This work contributes to improving the research capabilities of RAP and RIKEN. In accordance with the previous recommendation, the team has been strengthened by securing support team personnel and introducing new equipment to the machine shop, which is highly commendable to enhance the R&D performance of RIKEN and to show the standpoint of RIKEN as a leading facility for Japanese science and technology.

(4) Recommendation

The reinforcement of the support team in terms of personnel and the introduction of new equipment in the machine shop are highly commendable. Constant support and action are also requested in the future. Sustainability is most important.

We have a recommendation regarding the research structure of the D3 and D4 teams. Optical science is a field where science and technology develop through mutual stimulation. On the manufacturing technology side, it is important to develop original and novel processing technologies. This will realize novel optical elements and systems that have not been manufactured and constructed before. In the longer term, this will significantly raise the scientific performance of not only the D group but also of RAP and RIKEN as a whole. From this perspective, we recommend that the D group first examine the necessary processing technology from a long-term perspective and, based on the examined results, enforce the R&D system to have a sub-team for research of the processing method itself that should be a truly original.