Cross-ministerial Strategic Innovation Promotion Program (SIP)

Photonics and Quantum Technology for Society 5.0

Research and Development Plan

August 8, 2019

Director General for Science, Technology, and Innovation

Cabinet Office

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Process Chart

Overview of the Research and Development Plan

1. Significance and Targets

A cyber-physical system (CPS) that seamlessly fuses cyberspace (virtual space) with physical space (real space) is the key to realizing Society 5.0, which is a human-centered society that pursues both economic advancement and the resolution of social problems. However, although investment in smart manufacturing using IoT and AI technologies has begun, some bottlenecks are impeding investment in society and industry. To clear these bottlenecks, this SIP will leverage Japan's strengths in photonics and quantum technologies. From among these technologies, the SIP has carefully selected important and high-priority technologies in laser processing, photonic quantum communication, and photonic and electronic information processing to implement its development plans. This approach will accelerate the realization of Society 5.0.

2. Research and Development Themes

The main research and development themes are as follows.

(1) Laser processing (development of a CPS-type laser processing system to regain a leading share in the laser processing market)

(2) Photonic quantum communication (social implementation of quantum cryptography as a service that provides unbreakable security)

(3) Photonic and electronic information processing (advanced verification and social implementation of information processing that solves, for example, optimization problems at a speed that far surpasses that of conventional computers)

3. Implementation Structure

NISHIDA Naoto, the program director (PD), is in charge of creating and promoting the development plans. The Promoting Committee, which consists of experts from related ministries and agencies, controls the SIP comprehensively, with the PD serving as the chair and the Cabinet Office as the secretariat. The Promoting Committee utilizes the Management Expenses Grants provided by the National Institutes for Quantum and Radiological Science and Technology (QST) under the Ministry of Education, Culture, Sports, Science and Technology (MEXT) to recruit research leaders. The QST manages the progress of development.

4. Intellectual Property Management

The Intellectual Property Committee has been established under the QST to secure incentives for inventors and entrepreneurs and increase the benefits to the nation through the appropriate management of intellectual property.

5. Assessments

Before the Governing Board conducts its annual assessment at the end of the fiscal year, research leaders and the PD conduct self-inspections to make autonomous improvements to the SIP.

6. Harvesting Strategy

To ensure social implementation of development achievements, by releasing as much information to domestic/overseas enterprise networks and providing as many test platforms to collect technological data as possible, the SIP will feedback enterprises' assessment and adoption examples to the R&D activities to promote commercialization. At the same time, the R&D achievements will be publicized proactively and strategically so that they are disseminated throughout not only the enterprise communities but also society as a whole.

1. Significance and Targets

(1) Background and domestic/overseas situation

A cyber-physical system (CPS) that seamlessly fuses cyberspace (virtual space) with physical space (real space) is the key to realizing Society 5.0, which is a society that is centered on each and every person and pursues both economic advancement and the resolution of social problems. In the Japanese and overseas markets, active investment has already begun in the smart manufacturing field, which involves the specific application of IoT and AI technologies, so the act of constructing a CPS is underway.

However, causes for concern in relation to the expected promotion of this trend are becoming apparent. In the fields of IoT and AI, for example, there is no guarantee that, as required by future markets, electronic equipment equipped with control, communication, and AI devices will advance as expected (i.e., reduction in the factor of costs and performance). Similarly, it is unclear in the smart manufacturing field whether manufacturing will be transformed into network-type manufacturing systems. Moreover, the incidence of security threats in cyber space is rising constantly, and there are growing concerns that, once a disturbance occurs, its impact may cause enormous damage to the physical space.

Because these concerns may give rise to bottlenecks that discourage private companies from investing in the future, the national government needs to accelerate R&D activities to eliminate such obstacles and provide guidance to related industries so that these companies feel reassured enough to continue or expand their investments.

Outside Japan, multiple nations are strenuously promoting the IoT society and CPS through initiatives such as the Industrial Internet in the US, Industrie 4.0 in Germany, and Made in China 2025 in China to eliminate the above concerns. There are concerns that this may mark a drop in Japan's international competitiveness.

(2) Significance and political importance

Photonics and quantum technologies are positioned as core technologies that offer advantages in creating new value under the Fifth Science and Technology Basic Plan, and Japan has an advantageous position in this field. It is important that we leverage this advantage to clear the bottlenecks that are impeding the investment required for the realization of Society 5.0, promote investment by private companies, and then improve our international competitiveness in related fields.

With this in mind, the SIP has selected three important and high-priority development items from among the wide range of photonics and quantum technologies: (1) laser processing, (2) photonic quantum communication, and (3) photonic and electronic information processing.

For example, although there is strong demand for the development of a CPS for laser processing in the field of smart manufacturing, laser processing is actually one of the most difficult processes to establish a physical model for because it involves complicated physical phenomena. By establishing a CPS for laser processing, this SIP aims to lead the way in demonstrating that almost all types of manufacturing equipment can be transformed into smart systems. Such an achievement will surely accelerate investment in smart manufacturing and achieve significant improvements in productivity at every manufacturing site.

Furthermore, in Society 5.0, personal information with a high degree of secrecy and corporate information with a high business value will be generated in the fields of not only smart manufacturing, but also smart mobility, smart energy, and smart medical care. These types of information must be circulated and backed up securely. To realize Society 5.0, it is important to establish a quantum secure cloud technology by combining truly unbreakable quantum cryptographic communication technologies and secret-sharing backup technologies so that companies and users can feel secure enough to share, store and use various types of important information.

In light of this, continuing to clear the investment bottlenecks by developing photonic quantum technologies can help accelerate investment aimed at realizing Society 5.0 and make a significant contribution to improving Japan's competitiveness.

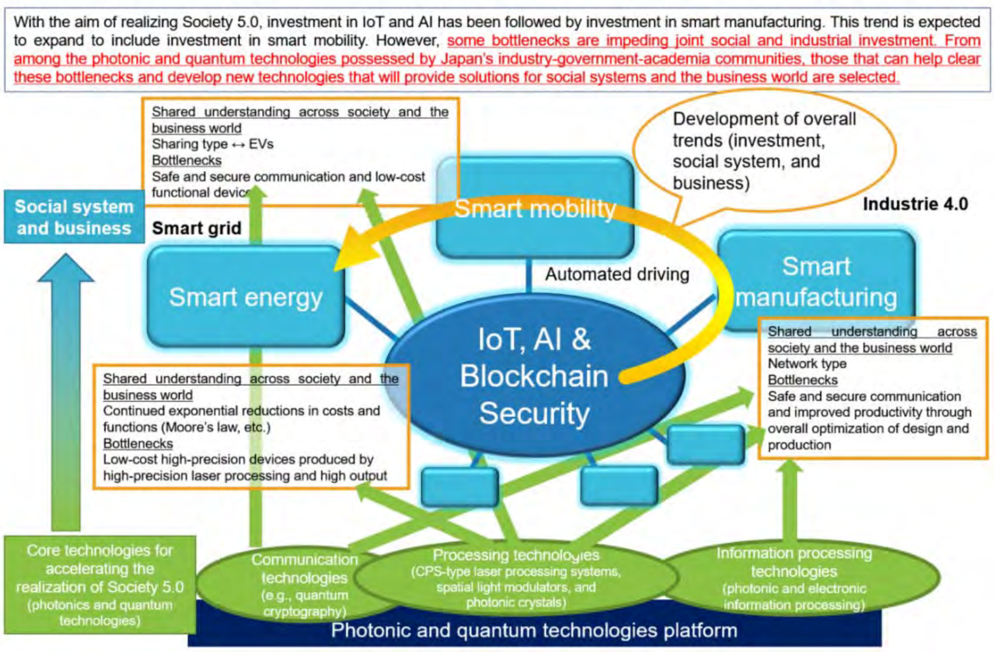

Figure 1-1: Overall background to photonics and quantum technologies for Society 5.0

(3) Targets and Goals

(i) Realizing Society 5.0

The SIP will clear bottlenecks that are impeding the investment required for the realization of Society 5.0 by leveraging Japan's strengths in photonic quantum technologies, specifically laser processing, photonic quantum communication, and photonic and electronic information processing. This SIP will implement initiatives designed to eliminate bottlenecks to investment in smart manufacturing such as the following: (1) installing CPS-type laser processing systems (thereby reducing the lead-time in the establishment of parameters for laser processing by 90%); (2) developing a quantum cryptographic technology that will facilitate the secure distribution, storage and utilization of data without exposure to cyber security threats for a long time to come (thereby developing quantum cryptographic devices that cost a quarter of conventional options); and (3) developing a next-generation accelerator platform constructed by utilizing various optimally arranged computing technologies, such as Ising computers, noisy intermediate-scale quantum (NISQ) computers, and fault-tolerant quantum computers, to facilitate the practical use of technologies that enable the optimal installation of whole applications that contribute to the realization of Society 5.0 (thereby raising the speed by 10 to 100 times). Consequently, this SIP is aimed at contributing to the establishment of a network-type manufacturing system that will qualitatively revolutionize manufacturing productivity. By clearing such bottlenecks, this SIP will initiate a trend (in investment, social systems, and business development) toward smart manufacturing, smart mobility, and smart energy to which private companies can practically apply their IoT and AI technologies, thereby helping to accelerate the realization of Society 5.0.

(ii) Social targets

To construct the CPS that is essential to realizing Society 5.0, the SIP will conduct R&D related to laser processing, photonic quantum communication, and photonic and electronic information processing in an effort to contribute to the establishment of a network-type manufacturing system by using CPS-type laser processing. This SIP will also conduct R&D for quantum cryptography with the aim of providing a quantum secure cloud service that will facilitate the secure storage of data backups and the secondary usage of highly confidential data, where information with a high degree of secrecy, such as personal information, cannot be decoded or illegally falsified on an computer even if advances are made in cryptanalysis and cyberattack techniques in the future. The SIP will establish a system platform as a next-generation accelerator that utilizes a wide range of computer types—including Ising computers (quantum annealing machines and classical technology-based annealing machines), NISQ computers, and fault-tolerant quantum computers—and then use these computing technologies optimally to clear the bottlenecks that are impeding the realization of Society 5.0.

Through measures such as those described above, this program will accelerate investment by private companies toward the realization of Society 5.0 in smart manufacturing and other fields that contribute to enhancing the sustainability of Japan's industrial competitiveness, thereby promoting economic advancement and the safety and security of Japan and its citizens to realize a rich, high-quality society.

(iii) Industrial targets

As described earlier, this SIP aims to realize a network-type manufacturing system by using CPS-type laser processing and contribute to improved productivity in the manufacturing industries by clearing the investment bottlenecks in the field of smart manufacturing through R&D related to laser processing, photonic quantum communication, and photonic and electronic information processing.

In addition, this SIP aims to improve Japan's competitiveness in various fields, including the automobile and medical industries, by implementing technological initiatives such as the following: (1) pursuing near-term applications (e.g., in sensing, medicine, and life sciences) for photonic crystal surface emitting lasers (PCSELs), which offer greater brightness and superior performance in comparison to existing semiconductor laser technologies, during the course of developing ultra-small laser processing systems; and (2) facilitating the practical use of quantum secure cloud systems to improve security in the exchange and management of personal information with a high degree of secrecy, such as the medical inspection data held by medical institutions.

(iv) Technological targets

Laser processing

This SIP will develop a CPS-type laser processing system that can be used in the manufacturing equipment required to ensure high precision and high-throughput and to perform complicated controls in accordance with the relevant material. More specifically, this system will deliver advanced real-time optical controls by the previous processing records and the measurement values. As the first step after that, it will be implemented in electronic device manufacturing processes, such as those for dealing with processing resistant materials in the manufacture of electronic components.

In addition, high-performance spatial light modulator devices (high light-resistance, high speed, and high integration) will be developed to facilitate the practical use of high-precision and high-throughput processing techniques including nonthermal laser processing. Moreover, the brightness of PCSELs will be increased to 1 $GWcm^{-2}sr^{-1}$ and their near-term application in compact smart sensing systems, including light-detection and ranging (LiDAR), will be demonstrated. PCSELs and their related technologies will finally be established as light sources for the aforementioned laser processing system in the future.

Photonic quantum communication

By developing a quantum secure cloud system, this SIP will develop a data distribution, storage and utilization network platform that will prevent security being compromised even if advances are made in cryptanalysis and cyberattack techniques. As the first step after that, it will perform demonstrations to apply the system mainly in the medical field (electronic medical records, genome analysis information, and smart manufacturing).

Photonic and electronic information processing

This SIP will develop a next-generation accelerator platform that makes optimal use of conventional accelerators (e.g., graphics processing units [GPUs]) and next-generation accelerators (e.g., Ising computers, NISQ computers, and fault-tolerant quantum computers) for each application domain and will then perform demonstrations that apply the platform in various fields, such as smart manufacturing, logistics, materials, and the energy and environment industries.

(v) Institutional targets

To prepare an environment in which companies can feel secure enough to manufacture or provide devices and services based on quantum cryptography, this SIP will promote standardization activities related to physical random number generators and quantum cryptography, create documents on safety assurance standards and evaluation methods, and then propose them to Japanese and international standardizing body.

At the same time, the SIP will construct an ecosystem model for the operation of assessments, inspections and certification in the future and put together a system design proposal that will be submitted to related ministries, agencies, advisory committees, and other government offices.

(vi) Global benchmarks

Laser processing

► Laser light sources with a wavelength that ranges from UV to near infrared will be introduced for installation on the CPS-type laser processing system taking into consideration future demand for laser processing systems. As a result, this SIP will establish a system that can also accept a quasi-general purpose-processing model that corresponds to a specific processing method based on a quantum physics model or other theories for which research is more advanced in Japan than it is in Europe. (Table 1-1)

► Maintaining Japan's current advantage compared to Europe and the US with respect to high-precision phase modulation characteristics (e.g., sensitive areas, efficiency of light utilization, and flatness) that are important in the development of spatial light modulator devices, this SIP will achieve greater light resistance (expanding the sensitive areas) and expand the available wavelength region (to include UV). (Table 1-2)

► PCSELs have already achieved the world's highest level of brightness among semiconductor lasers (Table 1-3). With the aim of utilizing these lasers as light sources for ultra-small processing systems in the future, this SIP will establish a device technology that delivers a level of brightness (1 $GWcm^{-2}sr^{-1}$) that is nearly as high as that of large fiber lasers and CO_2 lasers. (Note: This achievement will serve the needs of various fields other than just processing.) In addition, ahead of Europe and the US, this SIP will develop a light source that simultaneously possesses a narrow divergence angle, a narrow lasing spectra, and a high output power, all of which are unattainable with other light sources (Table 1-4), and will also establish a technology that enables the electronic scanning of the output beam direction at a high speed (of several MHz) that is faster than that available with mechanically driven methods (several kHz) (Table 1-4 and 1-5).

Main development organization	Japanese institution	German institution
Main light source (example)	From UV to near infrared	Near infrared
Features	This system constructs a quasi-general purpose processing model that corresponds to a specific processing method based on a quantum physics model, a stored database, and an artificial intelligence technology. It replies the capabilities of equipment to the cyber side in a short time.	This system constructs a processing model dedicated to a specific application for each object to be processed based mainly on a classical physics model and a stored database. It quickly replies the capabilities of equipment to the cyber side.
Development phase	Under development	The system is under development and the models are under construction.

Table 1-1: Development of CPS-type laser processing systems

Product (manufacturer)	Japanese company	German company	US company
Sensitive area (mm^2)	16 × 12	15.4 × 8.6	7.68 × 7.68
Sensitive area ratio (%)	98	87	83.4
Efficiency of light utilization (%)	87–95	59–63	62
Flatness (λ)	1/20	1/10	1/7 to 1/12
DAC bits	12	8	8
Linearity	High	Middle	Low
Capable wavelength region	From visible to infrared	From visible to infrared	From visible to infrared

Table 1-2: Development of spatial light modulation techniques

Development institution/ participating company	Japanese institution	US companies, etc.	US companies, etc.	(for reference) US companies, etc.	(for reference) Japanese companies, etc.
Laser type	Photonic-crystal surface-emitting laser (PCSEL) Single broad-area device	Vertical-cavity surface-emitting laser (VCSEL) Array device	Semiconductor laser (Fabry-Perot type) Single broad-area device	Fiber laser	Gas laser
Output	5–10 W	5–10 W	5–10 W	> 1 kW	> 1 kW
Beam quality	$M^2 \approx 2$	M^2 = Several dozen	M^2 = Several dozen	$M^2 \approx 10$	$M^2 = 1$
Brightness	~300 MW/cm^2sr	~5 MW/cm^2sr	~5 MW/cm^2sr	~1000 MW/cm^2sr	~1000 MW/cm^2sr
Features	• Narrow-divergence beam pattern (=collimated beam) • Higher output power with a larger area (maintains beam quality)	• Large-divergence beam pattern • Higher output power with a larger area (degrades beam quality)	• Large-divergence beam pattern with large asymmetry and astigmatism • With array, output power can be increased, but beam quality degrades further	• System with large size • High output power • Component service life: Several years	• System with large size • High output power • Component service life: Several years

Table 1-3: Development of semiconductor lasers (processing)

Development institution/ participating company	Japanese institution		German company, etc.
Type	Photonic-crystal surface-emitting laser (PCSEL)		Semiconductor laser (Fabry-Perot type)
Light emission form	Unidirectional surface emission (first target technology)	Scannable (future technology)	Edge emission
Peak output power	30 W or more (possibility)	Several W to 10 W or more (possibility)	75 W
Divergence angle	0.2° or less	0.5° or less	10–30°
Wavelength stability	0.08 nm/℃		0.27–0.28 nm/℃
Features	• High output power with a small beam divergence angle • External optics for collimation not required	• Electronic 2D scanning available • External optics for collimation not required	• Complicated external optics for collimation required • No native beam scanning possible • Stacking available; high slope efficiency
Scanning method	Mechanical	Electronic	Mechanical
External optics for scanning	Required	Not required	Required

Table 1-4: Development of photonic crystal lasers

Development institution/ participating company	Japanese institution	US company, etc.	German company, etc.	German company, etc.	US company, etc.
Type	PCSEL scanning (future technology)	Optical phased array (many difficulties)	Divided photodetectors	MEMS	Motor driven mechanism
Field angle	±50° or more (possibility)	120°	140°	60–210°	360°
Scanning method	Electronic	Thermal	–	Mechanical	Mechanical
Scan speed	MHz or more (possibility)	× (several dozen kHz)	– (no scan)	× (several dozen kHz)	× (several kHz)

Table 1-5: Development of methods for driving photonic crystal lasers

Photonic quantum communication

► In addition to promoting secure communication, this SIP will also develop a quantum secure cloud technology with metropolitan area network coverage that enables secure data storage that is unique to Japan's systems. (Tables 1-6 and 1-7)

Development institution	Japanese company (1)	Japanese company (2)	Swiss company (1)	Swiss company (2)	US company
Maximum communication distance	90 km	100 km	50 km	100 km	140 km
Key distribution speed (example)	0.3–1 Mbps @ 50 km	10 Mbps @ 10 km	Up to 1 kbps @ 20 km	> 3 kbps @ 50 km	Up to 100 bps @ up to 140 km

* Benchmarks for cryptographic communication using optical fibers

Table 1-6: Development of quantum cryptography

Development institution/ participating company	Japanese company, etc.	British company, etc.	Chinese company, etc.
System	Tokyo QKD Network (since 2010)	Quantum Communication Hub (under construction)	Quantum Backbone (since 2017)
Network coverage range	100 km range / 6–8 nodes	200 km range / 10 nodes	2,000 km range / 32 nodes
Key distribution speed	300 kbps/link	300 kbps/link	20 kbps/link
Function	Secure communication + **secure data storage**	Secure communication	Secure communication
Features	**Information theoretically secure distributed data backup function is under test operation**	Quantum cryptographic network using the latest optical communication network control (network virtualization) technique is under construction	World's largest (2,000 km) quantum cryptographic network has been constructed

Table 1-7: Trends in quantum network services

Photonic and electronic information processing

► Some acceleration technologies have been developed that deal with specific problems by using specific next-generation accelerators and conventional accelerators (Table 1-8). This SIP will develop a next-generation accelerator platform technology as an upper layer for these accelerators to enable application programs to use optimum acceleration.

Development institution	Japanese institution	Japanese company (1)	Japanese company (2)	US institution (1)	US institution (2)	Canadian company
Accelerator	Next-generation accelerator (future technology)	Multiple Ising computers	Multiple Ising computers	Conventional accelerator	Conventional accelerator/ next-generation accelerator in part	Specific Ising computer
Auto/manual	Auto (future technology)	Manual	Partially auto	Partially auto	Partially auto	Partially auto
Target problem	General purpose	Combination optimization problem	Combination optimization problem	General purpose	General purpose	Combination optimization problem

Table 1-8: Japanese and overseas next-generation acceleration technologies

(vii) Cooperation with municipalities

This SIP will cooperate with local municipalities in relation to their policies for industrial development. Through the transfer of technologies that include this SIP's achievements, this SIP will contribute to industrial advancements and the creation of added value.

2. Specific Research and Development

To construct the CPS that is essential to realizing Society 5.0, this SIP will conduct R&D related to laser processing, photonic quantum communication, and photonic and electronic information processing, all of which leverage photonics and quantum technologies, to contribute to the establishment of a network-type manufacturing system by using laser processing. More specifically, the SIP will develop technologies such as the following: (1) a CPS-type laser processing system that identifies optimal processing conditions through simulations and performs the processing accordingly; (2) a spatial light modulator technology for performing high-quality laser processing with a high throughput; (3) a compact energy-saving photonic crystal laser with a high beam quality that can be applied to a sensing light source and other such uses; (4) a quantum cryptography technology for ensuring safe and secure communication within a network-type manufacturing system; and (5) a high-speed optimization technology for processes and other elements of a network-type manufacturing system.

During this R&D, the SIP aims to facilitate the social implementation of systems that leverage the characteristics of the individual technologies for each research program while attempting to construct the above-mentioned network-type manufacturing systems.

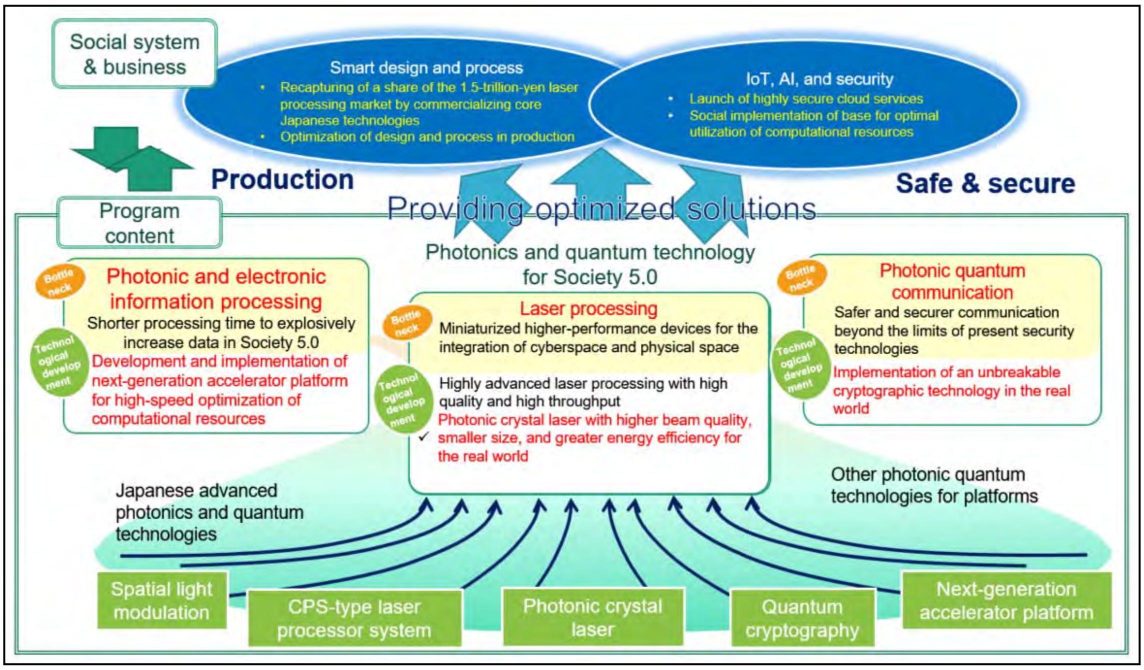

Figure 2-1: Overview of R&D into photonics and quantum technologies for the realization of Society 5.0

A cyber-physical system (CPS) that seamlessly fuses cyberspace with physical space is the key to realizing Society 5.0. Although investment in IoT, AI, and smart manufacturing has already begun, bottlenecks such as the lack of prospects for the migration to network-type manufacturing systems and the increasing incidence of security threats in cyberspace are impeding investment across society and industry in the smart manufacturing field. From among the various types of important and high-priority photonics and quantum technologies, this project **utilizes laser processing (to realize smart manufacturing through CPS-type laser processing), photonic quantum communication (to facilitate the secure distribution, storage and utilization of data in cyberspace), and photonic and electronic information processing (to allow the overall optimization of design and production in manufacturing)**. Our aim is to lead the way in demonstrating the application of a CPS in laser processing, which is actually one of the most difficult processes to apply a CPS to because it involves complicated physical phenomena, and prove that almost all types of manufacturing equipment can be transformed into smart systems. This project will initiate a trend (in investment, social systems, and business development) toward smart manufacturing and other such technologies to **contribute to the establishment of a network-type manufacturing system by using CPS-type laser processing** and eventually the realization of Society 5.0.

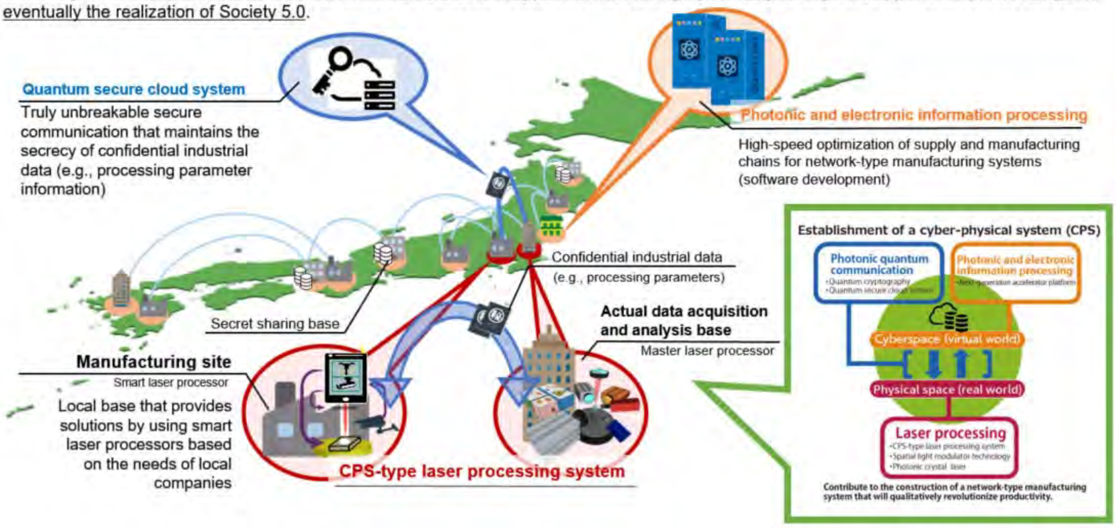

Figure 2-2: R&D items and their relationships

(1) Laser processing

Deputy PD: YASUI Koji (Senior Chief Engineer, Industrial Automation Market Div., Factory Automation Systems Group, Mitsubishi Electric Corporation)

Participating organizations: The University of Tokyo, Hamamatsu Photonics K.K., Utsunomiya University, Kyoto University, Mitsubishi Electric Corporation, and ROHM Co., Ltd.

Although there is strong demand for the development of a CPS for laser processing to facilitate the realization of Society 5.0, laser processing is actually one of the most difficult processes to establish a physical model for because it involves complicated physical phenomena. We will attempt to apply the CPS to laser processing to demonstrate that most of manufacturing equipment can be made smarter, ahead of others. Such an achievement will surely accelerate investment in smart manufacturing and achieve significant improvements in productivity at every manufacturing site.

To implement this, the SIP aims to establish a base for promoting the systematization of laser processing machines equipped with a CPS with a focus on the system integration of a Meister laser processing machine and a smart laser processing machine, as detailed in the description for each of the following research items.

For the establishment of such a base, the SIP will obtain technologies such as the underlying technologies required for the conducting of social demonstrations at the base as well as data communication, protection, and analysis technologies as the achievements of other R&D items (photonic quantum communication and photonic and electronic information processing) under the SIP or on the market.

This SIP also aims to apply themes that can be isolated as underlying technologies at an early stage, such as the LiDAR light source in the photonic crystal field, to facilitate their prompt social implementation.

(i) R&D for a CPS-type laser processing system

Lead researcher: KOBAYASHI Yohei (Professor, Institute for Solid State Physics, The University of Tokyo)

Participating organizations: The University of Tokyo, Kyushu University (in charge of proof of concept), and Gigaphoton Inc.

Collaborating organizations: Purdue University (in charge of proof of concept)

Summary of R&D:

In the manufacturing of electronic devices that are mounted in state-of-the-art electronics, laser and other forms of beam processing are being used increasingly often in addition to the application of semiconductor and substrate processing for semiconductor devices. In fact, the use of laser processing is indispensable for some state-of-the-art manufacturing lines, and there is strong demand for its application in a wider range of uses. However, the extraction of processing parameters to ensure that such processing can be applied as required is still largely dependent on people's experience and instinct. As a result, new processes are not being developed at the required speed. This R&D program demonstrates the use of a CPS-type laser processing system that significantly reduces the time required for the extraction of such parameters. More specifically, the SIP is employing the latest light source technology, optical element technology, optical operation technology, processing system technology, measurement and evaluation technology, calculation technology, and other such technologies to develop the following: a laser processing system that automatically changes parameters (i.e., a laser processing system with automatically variable parameters), a laser processing and measurement system for collecting and learning from data on past performances, and a parameter extraction system. As initial processing targets for demonstrations, this SIP selects materials that will help clear the bottlenecks that are impeding advances and cost reductions in the manufacturing of electronic device parts that are essential to the promotion of Society 5.0 (e.g., difficult-to-process materials in the manufacturing of electronic parts). After that, the SIP establishes the foundations required to include other materials and processing in the target range. Work is also conducted to advance the methods used to establish and verify a physical model for processing, thereby supporting the realization and progression of the application of a CPS in laser processing.

More specifically, this SIP creates a multifunctional high-speed Meister laser processing machine equipped with a site observation function as a laser processing and measurement system for collecting and learning from data on past performances. The SIP also creates a smart laser processing machine as a laser processing system with automatically variable parameters for field processing. A parameter extraction system links these two processors to extract the parameters required for laser processing. This R&D program has developed this system by integrating a Meister laser processing machine and a smart laser processing machine and forming a base to promote the systemization of laser processing machines equipped with a CPS with a focus on system integration.

This SIP is also attempting to create a laser processing CPS application base (social implementation) more efficiently and to accelerate the realization of a network-type manufacturing system by sharing its expertise of using the above processes in the building of a CPS promotion base with organizations that possess the basic underlying technologies for other laser processing processes and want to purse the industrial application of a CPS in form of a proof of concept.

Specific research details:
This SIP implements a parameter search program based on a physical model, AI, and other technologies as the foundation for a CPS-type laser processing system. To this end, a base machine that automatically changes parameters, processes materials, and observes and records processing is being built. This machine consists of a parameter-variable light source, a processing operation unit with a large parameter variable region, various detailed observation and evaluation units, a real-time observation unit, and a system that centrally controls all of the equipment via computers.

For the light source, this SIP evaluates and implements a system that widely and dynamically changes the parameters within the practical operation range from infrared to ultraviolet, mainly targeting light sources in the short wavelength region, including the wavelength conversion method that uses nonlinear optical elements and the like, taking into consideration the trend of putting the latest technologies to practical use in relevant projects, such as the Project for the Development of Next-Generation Laser Technologies with High-Luminance and High-Efficiency conducted by the Ministry of Economy, Trade and Industry and the New Energy and Industrial Technology Development Organization (NEDO laser project). The reason for this is that the demand for light sources in the short wavelength region is expected to increase in the field of laser processing, and Japan has an advantageous position in relation to the development of such light sources. Although the basic light source parameters include the wavelength, luminance*, pulse width, and repetition frequency, the SIP also examines a wider range of parameters, such as the waveform in a pulse and the pulse burst pattern, in line with the evaluation progress. For the processing operation unit, the SIP implements the latest technologies for high-luminance light sources with a shorter pulse and wavelength as the optical operation system, sets wide control ranges for the scan speed, scan pattern, and other parameters, and designs a system for obtaining data in a wide parameter space that is suitable for machine learning and other purposes. Furthermore, the SIP utilizes a modular design for the foundation of the system described above, sequentially builds demonstration units for evaluating multiple promising combinations of light sources, detailed observation and evaluation units, and real-time observation units based on their operation and evaluation, and constructs a Meister laser processing machine that serves overall as a laser processing system for collecting and learning from data on past performances and a parameter extraction system. To apply the operation results in a demonstration unit for a laser processing system with automatically variable parameters (described later) that prioritize availability, it is important to associate the basic information obtained from real-time observation units with the more detailed information obtained from detailed observation and evaluation units. Because the mutually correlated information on its own may not necessarily be sufficient, the SIP establishes a collaboration system to resolve issues and conduct studies by utilizing theories and information on interactions between light and substances based on the basic physical property research conducted in projects such as Q-LEAP, conducted by the Ministry of Education, Culture, Sports, Science and Technology.

This SIP operates the above system, obtains processing data on the target materials and target processing (selecting those that have a significant impact on the market, such as difficult-to-process materials in the manufacturing of electronic parts) in a wide parameter region, and builds a database to correlate the processing parameters and results through machine learning and other such methods. For specific applications that have strong market demand, the SIP engages in the R&D required for the quantification of interactions between light and materials with the aim of creating a physical model for applying the CPS.

Furthermore, this SIP conducts a unit design of subset configurations for demonstrations that are tuned to the expected actual processing based on obtained insights rather than learning and implements a smart laser processing machine as a laser processing system with automatically variable parameters. The SIP limits the variable ranges of the parameters for the light source and processing operation unit used in this system to a sufficient extent as necessary, but focuses on availability, stability, and other features in the configuration. In addition, the SIP aims to offer a configuration that allows processing to be performed with parameters that are automatically optimized with the database and algorithms that are learned and built for each processing target in the learning system based on the necessary data from the real-time observation system.

To select more specific target materials and target processing, this SIP first focuses on glass, which shows promise as an ultrahigh-speed and high-density electronic circuit substrate in the era of IoT. A bottleneck that is impeding the application of through holes on the glass used for substrates (TGV) is cracks caused by the processing. The SIP also evaluates and examines the selection of ceramic, which is another type of material used in electronic circuits, materials for the electrodes used in batteries for electric vehicles, carbon fiber reinforced polymer (CFRP), and various composite materials. Furthermore, the SIP attempts to select the target materials promptly from aluminum, stainless steel, copper, titanium, and other substances for which demand is expected.

This R&D program first conducts R&D into a system with a boring CPS and then attempts to apply the results to a system equipped with a cutting CPS.

To develop a more specific framework for conducting the above research, the SIP has implemented a Meister laser processing machine at the Kashiwa Campus of the University of Tokyo and a smart laser processing machine at the Hongo Campus and connected them via a network line, based on the assumption that the results of this R&D program will be implemented in society and used as the foundation for examining the future construction of a network-type manufacturing system (Figure 2-(1)-(i)).

*Luminance: Light output per unit area and unit solid angle

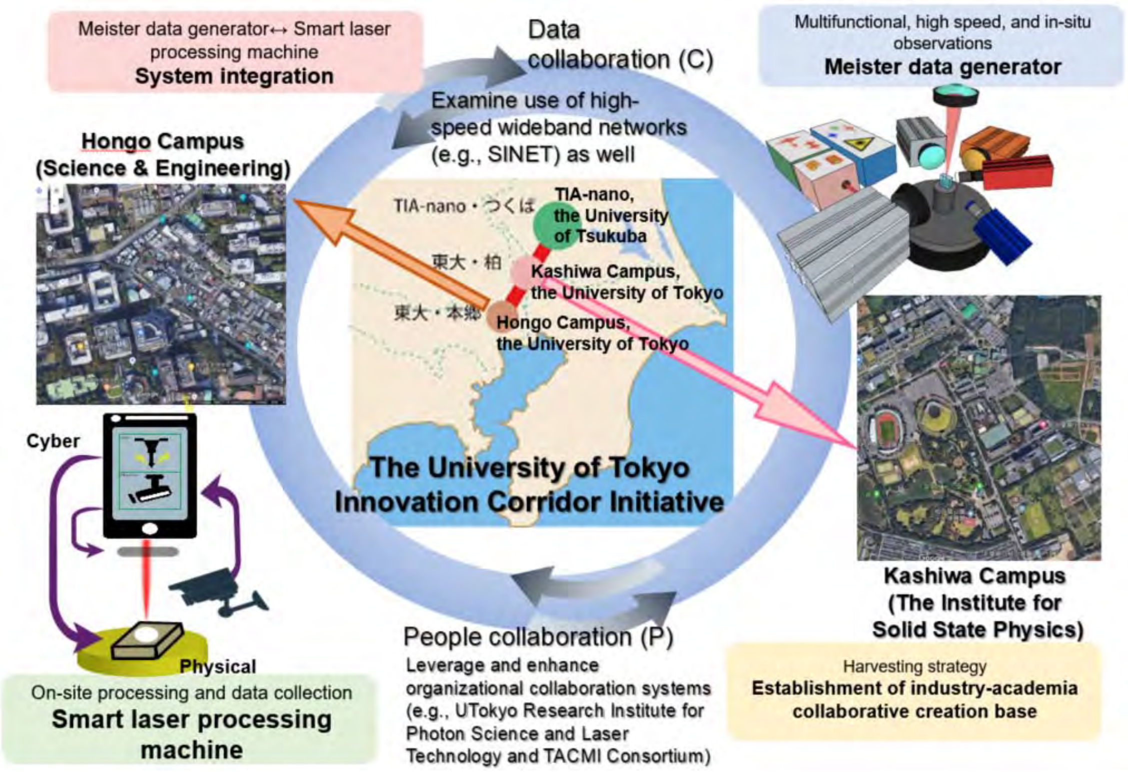

Figure 2-(1)-(i): Overall configuration of a smart manufacturing promotion base

To share expertise related to building a base for the application of a CPS, the specific steps taken for the SIP involved the development of a laser modification process for semiconductor materials at Kyushu University for the CPS system to prove the concept of the effect of expertise on the application of a CPS. The underlying technologies required to apply the CPS to this process are a processing technology, a measurement technology, an evaluation technology, and a simulation technology. These technologies were evaluated in collaboration with Gigaphoton Inc. and Purdue University (US), starting with the proposal of measures for extracting and overcoming challenges to apply the packaged expertise for the application of the CPS developed at the University of Tokyo and accelerate the creation of an industry-government-academia manufacturing ecosystem.

Social implementation:

For the social implementation of these systems, this SIP collaborates on the NEDO laser project and other such projects. More specifically, the SIP considered working with communities and other groups that were founded to collaborate widely with user companies such as the Consortium for Technological Approaches toward Cool Laser Manufacturing with Intelligence, which was mainly founded by corporations participating in the NEDO laser project. The SIP provides the equipment developed during this R&D program as a processing platform so that user companies and other participants can use this equipment to extract the processing parameters or for other purposes and reflect their evaluations in the R&D. Throughout this process, the SIP has considered the widespread acceptance of private resources in terms of people, materials, needs information, and evaluation information related to the R&D and marketing of the equipment.

This SIP also collaborates on Q-LEAP and other such projects and helps to promote the development of algorithms for estimating the optimal processing parameters, for which there is a strong demand in industry, by providing processing performance data. The SIP also creates a framework for updating the software used in this system based on the results of Q-LEAP and other such projects to establish a framework that will continue to meet these needs.

Furthermore, this SIP gives consideration to working with bases that study related themes in business-academia collaboration projects that began before this R&D program, such as the COI-STREAM Project conducted by the Ministry of Education, Culture, Sports, Science and Technology and the Japan Science and Technology Agency, and make sure that synergy is achieved from the results by extracting important challenges and sharing plans for the social implementation of systems and harvesting strategies and other types of data.

This SIP intends to raise social awareness of its results by demonstrating a CPS-type system for laser processing, which is inhibiting the application of a CPS with respect to the overall manufacturing process, to stimulate investment in smart manufacturing as a whole. More specifically, the SIP demonstrates processing—which is one of the most difficult processes to realize using conventional laser processing but is in great demand on the grounds of its high speed and flexibility (consequently, the application of lasers in such processing has a significant impact on industry)—in fields where the application of a CPS is in strong demand and future growth is expected. An example of this type of processing is the processing of difficult-to-process materials in the manufacturing of electronic parts. Furthermore, the SIP provides the results of this SIP for industrial fields where lasers are conventionally applied (e.g., cutting and welding) and new markets in which they are expected to be used in future (e.g., 3D printers and surface modifications) as necessary by collaborating on related projects with the aim of contributing to raising the levels of industries that require laser processing as a whole.

To provide a more specific means of smoothly transferring technologies developed by public organizations to industry, this SIP selects partner companies from existing private companies and venture companies (startup companies founded at universities or research organizations) and works with them on a business basis. This R&D program promotes the building of a framework in which the main modules to be designed and demonstrated are subcontracted in advance to partner companies that will implement them so that the companies that utilize the results can evaluate the technologies produced by this program at consortiums or other events and receive the same technologies as-is in the form of products, thereby spreading the research results across enterprises, including small and medium-sized companies.

In addition, to share expertise related to building a base for the application of a CPS, Kyushu University has taken the lead in establishing a laser modification process base to address future user needs based on an evaluation of the proof of concept results and help accelerate the process of making manufacturing smarter overall (creation of network-type manufacturing systems) through collaborations with the bases at the University of Tokyo. This demonstrates the application of a CPS in manufacturing technologies using lasers in multiple processes and accelerates private investment in smart manufacturing, thereby speeding up the social implementation of the results of this R&D.

Research goals:
Goals for FY2019

- Begin verifying a method for observing the processing process based on an evaluation of the underlying technologies for performing detailed observations, begin verifying a test model of the Meister laser processing machine, and design and build the smart laser processing machine. In addition, provide a test model of the Meister laser processing machine to the Consortium for Technological Approaches toward Cool Laser Manufacturing with Intelligence, discuss preparations for the trial operation, including the system, and then start its operation.

- With the aim of sharing expertise related to the building of a base for the application of a CPS, evaluate the underlying technologies required to apply the CPS to a laser modification process—in other words, a processing technology, a measurement technology, an evaluation technology, and a simulation technology—in collaboration with Gigaphoton Inc. and Purdue University (U.S.) and propose measures for extracting and overcoming challenges to apply the packaged expertise for the application of the CPS developed at the University of Tokyo.

Interim goals to achieve by FY2020

- Verify a system that remotely updates the functions of a laser processing system with automatically variable parameters based on information learned by a laser processing and measurement system for collecting and learning from data on past performances to improve the processing performance (TRL5).

Final goals to achieve by FY2022

- Aim to achieve TRL7 for the demonstration of a laser processing system with automatically variable parameters and TRL5 for the demonstration of a laser processing and measurement system for collecting and learning from data on past performances and verify a system that further improves the processing performance based on data collected in these systems. Attempt to reduce the parameter extraction time significantly using these results with the aim of reducing the lead-time by 90% when initially selecting the processing method.

Institutes and researchers for each R&D item:

(A) Item name: Development of a Meister laser processing machine (representative researchers: KOBAYASHI Yohei and TAMARU Hiroharu, the University of Tokyo)

Twelve school personnel, three graduate students, and some other additionally selected participants are involved in the development of the system and equipment and other such work.

Task A1: Development of prototype model

Task A2: Development of demonstration model

(B) Item name: Development of a smart laser processing machine (representative researchers: KOBAYASHI Yohei and TAMARU Hiroharu, the University of Tokyo)

Twelve school personnel, three graduate students, and some other additionally selected participants are involved in the development of the system and equipment and other such work.

Task B1: Development of prototype model

Task B2: Development of demonstration model

(C) Item name: Building of a base for the application of a CPS (representative researchers: TAMARU Hiroharu and KOBAYASHI Yohei, the University of Tokyo)

Twelve school personnel, three graduate students, and some other additionally selected participants are involved in the establishment of the collaboration framework and system development.

Task C1: Establishment of base

Task C2: Operation of base

Task C3: System development

(ii) R&D for a spatial light modulator technology

Lead researcher: TOYODA Haruyoshi (General Manager, Central Research Laboratory, Hamamatsu Photonics K.K.)

Participating organizations: Hamamatsu Photonics K.K. and Utsunomiya University

Summary of R&D:

A manufacturing technology that supports industry in Japan, laser processing is an integrated technology that consists of materials, a laser, light control, light measurement, and system integration, all of which are areas in which Japan has accumulated considerable expertise as a world leader in science and technology. Laser processing allows for advancements in the functionality of devices that link cyberspace and physical space as well as the high-precision processing of, among other things, highly functional materials that are difficult to process and can help realize Society 5.0 through contributions to smart manufacturing, smart mobility and other smart solutions. Given this, technologies capable of overcoming the bottlenecks in laser processing are highly anticipated.

More specifically, we need to meet a variety of needs, including the development of high-precision and high-throughput processing techniques to process new materials that are both lightweight and rigid, the adoption of complicated designs with a large number of curved surfaces, and a reduction in the lead-time for new products. In particular, carbon fiber reinforced plastic (CFRP), which has attracted attention for its use in transport machinery and other applications because it is lightweight and highly rigid, poses some challenges. For example, existing technologies cannot achieve a sufficiently high level of processing precision to cut CFRP cleanly because this material is extremely rigid and the processing shapes are limited. Consequently, CFRP users have high expectations for the use of laser processing, which offers high precision and a high throughput.

The aim of this R&D is to develop high-precision LASER processing with a high throughput into practical use (thereby raising the speed by 10 to 100 times), and perform other activities that contribute to the establishment of a network-type manufacturing system that will qualitatively reform productivity in the manufacturing industry. For these aim, we develop a spatial light modulator (SLM) that can control the two-dimensional phase distribution of light with a high degree of precision and its applied technologies. More specifically, we aim to increase the precision (larger area, support for ultraviolet light, higher acceleration, and greater integration) of a next-generation SLM, which will be the key to realizing multipoint simultaneous processing and die cutting processing technologies that surpass the concept of conventional laser processing by offering greater precision and higher speeds, and put a high-precision laser processing module that combines processing and measurements using this SLM into practical use by combining the power of industry, academia and government to realize the social implementation of such systems.

Specific research details:

The two main development items are described below. We are attempting to put a high-precision next-generation laser processing technology with a high throughput into practical use by realizing these development items.

1) Enhanced performance of photonics and quantum control devices (SLMs) that can be applied in industry

We will design an optimal reflective mirror, adopt a film forming technology that is optimal for transparent conductive films, and optimize liquid crystal materials for the main components of an SLM to realize a device that offers sufficient high-power-resistance for a liquid-crystal-type SLM to be able to withstand the use of a processing laser that has a high average power level. We will also develop SLMs for the wavebands used in laser processing, which range from near-infrared light to ultraviolet light, by optimizing the light modulation materials and components (i.e., a mirror, transparent conductive film, and non-reflective mirror) to demonstrate multipoint simultaneous processing. In addition, we will develop an SLM with a phase modulation function that has a much higher degree of precision by making improvements such as increasing the area for higher high-power-resistance, improving the flatness for higher precision, and using a semiconductor microfabrication technology for higher speed and integration with the aim of realizing high-power laser processing with a high throughput. For example, we will develop SLMs that support the non-thermal processing by ultrashort pulse laser processing, which has attracted attention for its use in the laser processing of difficult-to-process materials, and SLMs for microfabrication by ultraviolet light laser.

2) Development of photonics and quantum control modules (high-precision laser processing modules) that accelerate industrial applications

We will evaluate the light harvesting properties and material processing performance during beam pattern control for a laser light by using an SLM and a CW laser light source with an average power of 100 W or a short pulse laser light source with an average power of 10 W. After that, we will obtain the same data using a laser light source with a power level that has been enhanced for general industrial usage. We will build a laser processing machine using this SLM and laser light source and then confirm that the throughput can be improved by one or two orders of magnitude in comparison to conventional methods by controlling the beam pattern of the laser light according to the processing shape and target and optimizing the parameters. In the final stage, we will build the Platform for Practical Use Tests (tentative name) by conducting technology transfers to processor manufacturers and other companies with its practical use in mind and work with users and other parties to execute a processing test while targeting its practical use.

Social implementation:

We will attempt to establish a high-tech processing technology with spatiotemporal control and realize flexible switching between thermal processing and non-thermal processing as well as simultaneous three-dimensional multipoint processing to accelerate high-precision processing in manufacturing processes (raising the speed by about 10 to 100 times compared to existing processing technologies) and achieve various other improvements. By achieving the final goal of this R&D program, we will be able to deliver a processing technology that meets the needs of the automobile and semiconductor industries. We will establish the Platform for Practical Use Tests (tentative name; PF) as a user collaboration base at the Utsunomiya University Center for Optical Research & Education (CORE) and the Central Research Laboratory (HPK) of Hamamatsu Photonics to collect a wide range of information on the needs of user companies and begin testing and evaluating laser processing samples to pave the road to its practical usage and commercialization through user collaborations in both competing and partnership fields. To promote the widespread use of this technology, we will release the research results, advertise the PF, and perform other activities by attending symposiums and workshops hosted by the CORE and utilizing various forms of media (e.g., websites). We will also organize seminars and training sessions to develop engineers and human resources for R&D organizations and user companies.

Research goals:

A) Enhanced performance of photonics and quantum control devices (SLMs) that can be applied in industry

Goals in FY2019

• Prototype a device with an optimally designed pixel drive unit and components to improve high-power-resistance by one order of magnitude and realize an SLM with a phase control precision with a wavelength of 1/100 or less (FY2020) as well as conduct device evaluations and processing demonstration experiments.

• Prototype and evaluate the device to verify the principles of a high-speed SLM with a large area and expanded wavelength region.

Interim goals to achieve by FY2020

- Realize an SLM that has a light high-power- resistance that has been improved by more than one order of magnitude (average strength level: 100 W) and an improved phase control precision with 1/100 wavelength or less [TRL3]. Create a laser processing system with an embedded SLM based on the laser processing optical system built on an optical bench at Hamamatsu Photonics and its joint research partner, Utsunomiya University, and apply the system in demonstration experiments of multiple types of laser processing.

Final goals to achieve by FY2022

- Realize an SLM with a several times larger light control area realizing a high light high-power-resistance as well as a new-typed SLM that has a response speed that is higher by three orders of magnitude or more. (Using these SLMs will allows us to acquire the SLM manufacturing technology required to enhance the performance of high-power laser processing and improve productivity by about 100 to 1,000 times) (TRL7). As various tools that can be used under conditions similar to the actual usage conditions are available on the TRL7 level, we will provide them with a technology for integrating the light source, light control system, and measurement system to ensure that the functions of the SLM are sufficiently leveraged in the user's laser processing equipment.
- Realize laser processing with a high throughput. On the Platform for Practical Use Tests (tentative name), execute a processing test that is linked to needs (to promote the practical use of high-power laser processing) (TRL5).

B) Development of photonics and quantum control modules (high-precision laser processing modules) that accelerate industrial applications

Goals in FY2019

- Hamamatsu Photonics will develop a laser processing module. And more, Utsunomiya University will develop a laser processing platform and produce processing experiments for selected processing targets.

Interim goals to achieve by FY2020

- Perform laser processing with a module that combines a laser for general industrial usage with an SLM (TRL3). Perform a laser processing test that meets the needs identified from the results of an investigation performed using the prototyped laser processing machine to demonstrate the effectiveness of conducting processing with an SLM.

Final goals to achieve by FY2022

- Work with external users to produce laser processing demonstration experiments and improve usability (TRL3). Build a hologram database to incorporate processing needs and perform optimal processing by executing a laser processing test with external users on the Platform for Practical Use Tests (tentative name; Utsunomiya). Also in Hamamatsu, laser processing platform where users in Chubu district can test and feel the useful of CPS-type laser processing with SLM, will be built. Hamamatsu Platform will operate in cooperation with the Graduate School for the Creation of New Photonics Industries

Institutes and researchers for each R&D item:

Figure 2-(1)-(ii) provides an overview of the specific R&D and implementation framework.

(A) Item name: Enhanced performance of SLMs that can be applied in industry (representative researcher: TOYODA Haruyoshi, Hamamatsu Photonics)

Task A1: Realization of light-resistant device (person responsible for specific implementation: TOYODA Haruyoshi, Hamamatsu Photonics)

(1) Materials selection and optimal design for reflective mirror

(2) Production of transparent conductive film under optimal conditions

(3) Optimization of liquid crystal material

Task A2: Expansion of effective wavelength range (particularly the ultraviolet region) (person responsible for specific implementation: TOYODA Haruyoshi, Hamamatsu Photonics)

Task A3: Development of large-area SLM (person responsible for specific implementation: TOYODA Haruyoshi, Hamamatsu Photonics)

Task A4: Development of high-speed integration (person responsible for specific implementation: TOYODA Haruyoshi, Hamamatsu Photonics)

Task A5: Establishment and evaluation of SLM evaluation method (person responsible for specific implementation: HAYASAKI Yoshio, Utsunomiya University)

(B) Item name: Development of high-precision laser processing modules that accelerate industrial applications (representative researcher: KATO Yoshinori, Hamamatsu Photonics)

Task B1: Development of measurement method for high-precision laser processing (person responsible for specific implementation: KATO Yoshinori, Hamamatsu Photonics)

Task B2: Development of high-precision laser processing modules (person responsible for specific implementation: KATO Yoshinori, Hamamatsu Photonics)

Task B3: Development of Platform for Practical Use Tests (person responsible for specific implementation: HAYASAKI Yoshio, Utsunomiya University)

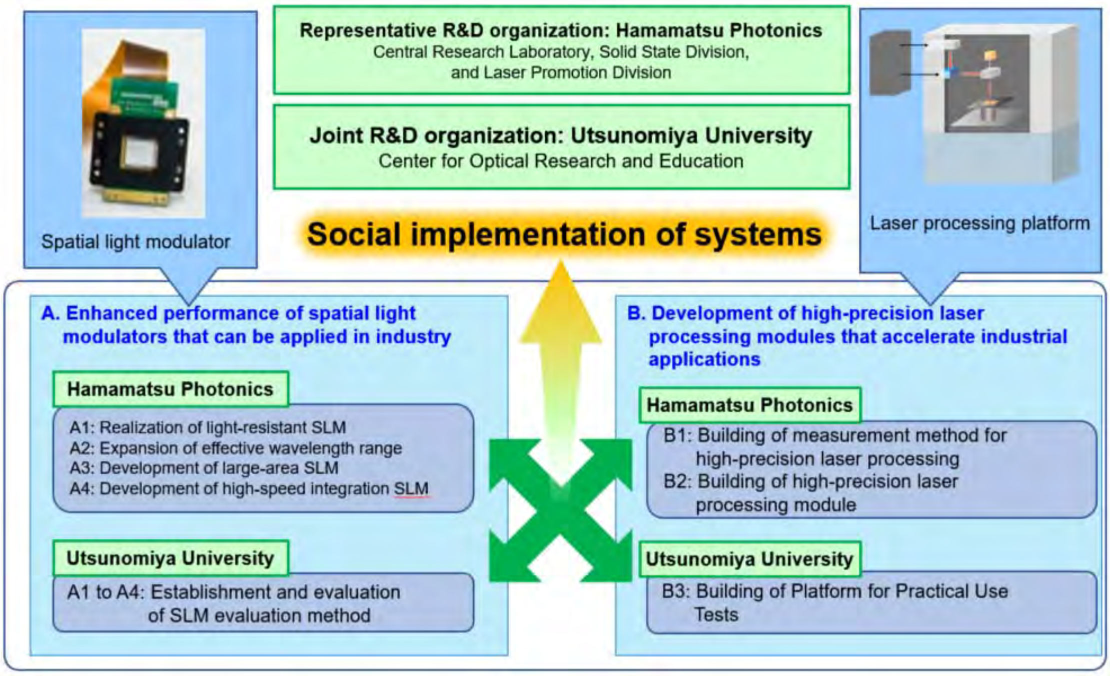

Figure 2-(1)-(ii): Overview and implementation framework for R&D

(iii) R&D for photonic crystal surface emitting lasers (PCSELs)

Lead researcher: NODA Susumu (Professor, Graduate School of Engineering, Kyoto University)

Participating organizations: Kyoto University, Mitsubishi Electric Corporation, and ROHM Co., Ltd.

Collaborating organizations: Hokuyo Automatic Co., Ltd. and other organizations

Summary of R&D:

Semiconductor lasers have excellent features, such as small device size, low costs, low power consumption, and high controllability. However, their brightness (up to 100 $MWcm^{-2}sr^{-1}$) has been limited to no higher than about one-tenth of that of other large-scale lasers. This limitation has made it difficult to realize highly compact and efficient processing systems using a semiconductor laser diode (LD) for applications in smart manufacturing, to develop smart, compact sensing technologies that support smart mobility, and to apply semiconductor lasers in medicine and life sciences to foster a healthy society. To overcome this limitation, the realization of a coherent oscillation of light over a large area is indispensable. The only semiconductor laser that can be expected to realize such an oscillation is the photonic crystal surface emitting laser (PCSEL), which was invented in Japan.

In this R&D program, we will advance this PCSEL technology with the aim of achieving high brightness (i.e., a higher output power together with a high beam quality). At the start of this SIP, PCSELs realized the highest brightness of any semiconductor laser in the world at 300 $MWcm^{-2}sr^{-1}$, which is triple the above-mentioned limit (100 $MWcm^{-2}sr^{-1}$) of conventional semiconductor lasers. We will attempt to establish a device technology for the achievement of a higher brightness of 1 $GWcm^{-2}sr^{-1}$. This technology is to be transferred to near-term applications, including sensing, medicine, and life sciences. We aim to develop PCSELs with a brightness of 1 $GWcm^{-2}sr^{-1}$ in nanosecond-pulsed operations and demonstrate their application in a smart, compact sensing system that supports smart mobility, which is important for the realization of Society 5.0. Furthermore, we will attempt to establish a foundational device technology that can deliver a high-brightness PCSEL in continuous-wave (CW) operations with the aim of facilitating future applications in smart processing. As a technological goal for the future, we will also promote activities aimed at developing smart PCSELs by, for example, adding electronic beam-scanning functionality.

Specific research details:

We will develop a technology that increases the brightness of PCSELs to 1 $GWcm^{-2}sr^{-1}$ and—as one of a variety of near-term applications—achieves high-brightness, nanosecond-pulsed operations for the purpose of facilitating sensing applications in smart mobility.

In addition, we will develop a foundational device technology for high-brightness CW operations and a beam-combining technology (achieving an output power of over 100 W) for smart processing (laser processing) systems that will support Society 5.0.

Furthermore, we will develop technologies that make PCSELs smart (i.e., electronic beam-scanning and beam-pattern optimization) in order to lay the foundation for further advancements for this unique laser that was invented in Japan and thereby maintain its technological superiority into the future.

Figure 2-(1)-(iii) provides an overview of the R&D and arrangements for its execution. In this R&D program, we will perform the following activities.

(A) Development of high-brightness PCSELs for pulsed and CW operations

A1: Establishment of a foundational device technology for higher laser brightness

(1) Advancement and optimization of photonic crystal (double-lattice) structures that facilitate high-power, high-beam-quality operations over a large area of coherent oscillation

(2) Control of the distribution of the injected current for operations with stable, high-quality beams

(3) Improvement of the upward light extraction efficiency and elimination of unnecessary absorption losses for high-efficiency operations

A2: Establishment of heat dissipation, packaging, and beam-combining technologies as well as large-area, one-chip, high-power device technologies for future applications in smart processing (laser processing)

A3: Development of a nanosecond-pulsed operation technology for application in sensing systems such as LiDAR

By developing underlying technologies such as those described above, we will attempt to realize high-brightness PCSELs and, as a near-term application, demonstrate their use in smart, compact sensing systems such as LiDAR.

(B) Development of smart PCSELs

B1: Establishment of structural designs and fabrication methods for PCSEL devices that enable beams to be emitted in arbitrary directions and development of two-dimensional matrix-driving technologies to facilitate electronic beam-scanning in two dimensions

B2: Development of device technologies for controlling the in-plane distribution of the injected current and investigation of methods for performing machine learning on the correlation between the current distribution and beam shape for the on-demand control of beam shapes through a machine learning (AI) technology

By developing technologies such as those described above, we will make PCSELs smart.

The R&D will be executed as follows: Kyoto University (representative R&D institute) will coordinate the SIP as a whole while also performing the design, fabrication, and evaluation of high-brightness PCSEL prototypes as well as conducting studies on how such lasers can be made smarter. Mitsubishi Electric (joint R&D institute (1)) will develop high-brightness PCSEL technologies (particularly for CW operations) and beam-combining technologies. ROHM (joint R&D institute (2)) will develop high-brightness PCSEL technologies (particularly for pulsed operations) and short-pulsed driving technologies. We will establish a center of excellence in the Photonics and Electronics Science and Engineering Center at Kyoto University to allow participating institutes to collaborate in conducting intensive R&D into PCSELs. Through this center of excellence, we will accelerate the social implementation of PCSEL technologies by transferring device technologies to non-participating companies and providing sample devices to user companies, including collaborating institutes.

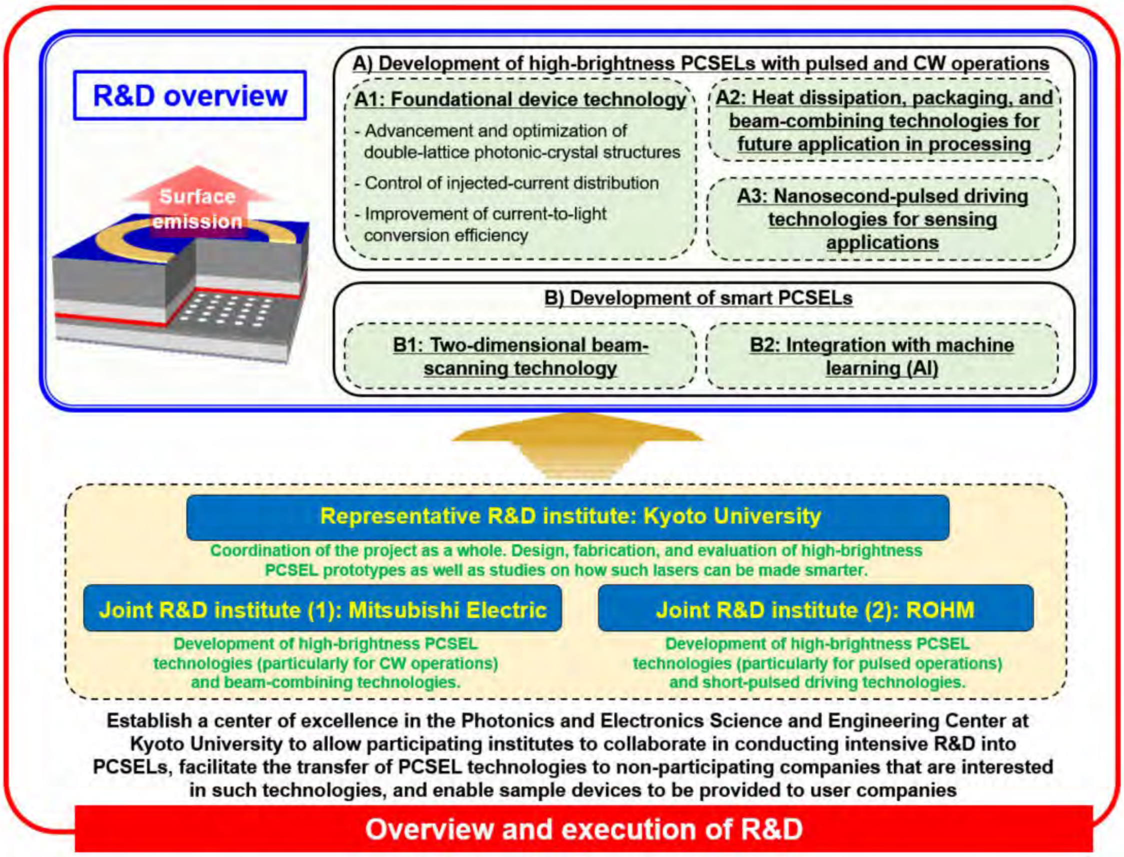

Figure 2-(1)-(iii): Overview and execution of R&D

Social implementation:

As this R&D program will demonstrate high-brightness PCSELs with nanosecond-pulsed operations as one of a variety of near-term applications, the social implementation of PCSELs with high directivity and stability in smart, compact sensing systems will be feasible. This achievement is expected to allow the technical issues affecting current sensing products (such as size, cost, and reliability) to be surmounted.

As the foundational device technology for high-brightness PCSELs with CW operations, together with a beam-combining technology, will also be established, the social implementation of PCSELs in a compact, low-cost processing system that offers a high efficiency and throughput is expected to be achieved within several years of the SIP's completion. These technologies are expected to be applied in on-demand smart processing in the future.

Furthermore, the development of smart PCSELs through the addition of an electronic beam-scanning technology will secure our market supremacy in a sustainable way now and into the future.

In the Photonics and Electronics Science and Engineering Center at Kyoto University, we will establish a center of excellence for conducting R&D into PCSEL technologies and pursue the social implementation of PCSELs by transferring device technologies to companies (other than participating institutes) that are interested in the results of this R&D while also providing such devices to the user companies. We will also consider various strategies, such as making intellectual property available to the public, with the aim of eliminating obstacles to the widespread commercialization of PCSELs.

Development goals:

(A) Development of high-brightness PCSELs for CW and pulsed operations

Goals in FY2019

To establish the underlying technologies required for higher brightness, we will further enhance the functionality of the double-lattice photonic crystal structure, develop a method for controlling the distribution of the injected current, and advance technologies for improving the slope efficiency using a DBR. Specifically, for "(A1) Foundational device technology," we aim to achieve the following: (1) fabrication of a double-lattice photonic crystal device capable of high-power, high-beam-quality operations over a circular oscillator area with a diameter of approximately 1 mm (whose design was completed in the previous fiscal year) to realize a brightness of 500 to 600 $MWcm^{-2}sr^{-1}$; (2) transformation of the injected current into a Gaussian distribution and clarification of the effects of this distribution on the beam quality; and (3) establishment of a technology for reliably achieving a slope efficiency of 0.7 W/A or higher. For "(A2) Heat dissipation, packaging, and beam-combining technologies," we will evaluate a prototype water-cooling package that is designed to maintain a device temperature of below 60°C during 50-W heat generation over a circular area with a diameter of approximately 1 mm and then produce a second prototype. We will also prototype a system for combining seven beams and evaluate various characteristics, such as the combined beam's diameter, divergence angle, quality, and robustness against mounting-position errors. In addition, we will fabricate the first one-chip device with a large circular area of 3 mm to 5 mm. For "(A3) Nanosecond-pulsed driving technologies," we will design and demonstrate a driver and package for the purpose of realizing short-pulsed operations with pulse widths of less than 10 nanoseconds. In addition, we will provide PCSELs to user companies, including collaborating institutes, and prototype a LiDAR system equipped with a PCSEL to accelerate the social implementation of PCSELs.

Interim goals to achieve by FY2020

Our interim goal is to establish an underlying technology for increasing the brightness of PCSELs to 1 $GWcm^{-2}sr^{-1}$. Specifically, for "(A1) Foundational device technology," we aim to achieve a large-area, coherent oscillation that enables a narrow divergence angle of less than 0.2° and a slope efficiency of 0.8 to 1.0 W/A, by establishing underlying technologies that include the following: (1) optimized double-lattice photonic-crystal structures; (2) optimized injected-current distribution controls; and (3) optimized upward extraction efficiency through control of the reflection phase of a DBR and suppression of the internal absorption loss. For "(A2) Heat dissipation, packaging, and beam-combining technologies," we will attempt to establish heat dissipation and packaging technologies capable of providing a heat resistance of less than 1°C/W, beam-combining technologies for PCSELS, and a fabrication method for large-area, one-chip, high-power devices. For "(A3) Nanosecond-pulsed driving technologies," we intend to build a nanosecond-pulsed driving circuit.

Final goals to achieve by FY2022

By integrating the above R&D results, we will attempt to achieve the following goals.

・Establishment of an underlying technology for the CW operation of PCSELs with high brightness (1 $GWcm^{-2}sr^{-1}$) and beam-combining technologies (TRL5) and clarification of the effectiveness of large-area, one-chip, high-power devices.

・Achievement of the nanosecond-pulsed operation of PCSELs with high brightness (1 GWcm-2sr-1) and realization of a PCSEL that does not require a beam-shaping optical system and has a high signal-to-noise ratio and a high tolerance for environmental changes in sensing applications (TRL7).

(B) Development of smart PCSELs

Goals in FY2019

• With respect to smart PCSEL technologies, we will investigate advanced photonic-crystal modulation schemes and basic technologies for arrayed structures for two-dimensional electronic beam-scanning and implement a driving method that uses a matrix transistor for fusion with machine learning. Specifically, for "(B1) Two-dimensional beam-scanning technology," we will evaluate devices fabricated by air-hole-retained regrowth based on the MOVPE method, develop a modulation scheme for increasing the slope efficiency, and develop a basic technology for arrayed structures. For "(B2) Integration with machine learning (AI)," we will fabricate a prototype PCSEL device with an integrated matrix transistor that can control the injected-current distribution and establish the foundation for a method of applying machine learning that will allow for the control of the beam shape.

Interim goals to achieve by FY2020

- The interim goal for the two-dimensional beam-scanning technology is to establish a PCSEL technology that will allow beams to be emitted in arbitrary directions. The interim goal for integration with machine learning (AI) is to establish an underlying technology by performing machine learning on the correlations between the various injected-current distributions and the beam shapes.

Final goals to achieve by FY2022

By integrating the above R&D results, we will attempt to achieve the following goals.

- Completion of the development of smart PCSEL technologies (integrated with electronic beam-scanning and machine learning) that will allow beams to be emitted in arbitrary directions using electronic controls and shaped using machine learning (TRL4).

Institutes and researchers for each R&D item:

(A) Development of high-brightness PCSELs for CW and pulsed operations

(Representative researcher: NODA Susumu [Kyoto University]; joint researchers: FUJIKAWA Shuichi [Mitsubishi Electric] and NAKAHARA Ken [ROHM])

A1: Establishment of foundational device technology for higher brightness

(Research institute: Kyoto University, Mitsubishi Electric, and ROHM; persons in charge: ISHIZAKI Kenji and YOSHIDA Masahiro [Kyoto University], SATAKE Tetsuya and AKIYAMA Koichi [Mitsubishi Electric], KUNISHI Wataru and MIYAI Eiji [ROHM], and eight other researchers)

A2: Development of heat dissipation, packaging, and beam-combining technologies for future applications in smart (laser) processing

(Research institute: Mitsubishi Electric and Kyoto University; persons in charge: KUBA Kazuki and SOTA Shinnosuke [Mitsubishi Electric], DE ZOYSA Menaka and YOSHIDA Masahiro [Kyoto University], and 11 other researchers)

A3: Development of nanosecond-pulsed operation technologies for sensing applications, such as LiDAR

(Research institute: ROHM and Kyoto University; persons in charge: KUNISHI Wataru and MIYAI Eiji [ROHM], DE ZOYSA Menaka and ISHIZAKI Kenji [Kyoto University], and five other researchers)

(B) Development of smart PCSELs

(Representative researcher: NODA Susumu [Kyoto University]; joint researchers: FUJIKAWA Shuichi [Mitsubishi Electric] and NAKAHARA Ken [ROHM])

B1: Electronic beam-scanning technology

(Research institute: Kyoto University and ROHM; persons in charge: ISHIZAKI Kenji and SAKATA Ryoichi [Kyoto University], KUNISHI Wataru and MIYAI Eiji [ROHM], and five other researchers)

B2: Integration with machine learning (AI)

(Research institute: Kyoto University; persons in charge: DE ZOYSA Menaka and YOSHIDA Masahiro [Kyoto University], KUBA Kazuki and NIIKURA Eiji [Mitsubishi Electric], and five other researchers)

(2) Photonic quantum communication

Deputy PD in charge: SASAKI Masahide

(Distinguished Researcher, Advanced ICT Research Institute, National Institute of Information and Communications Technology)

In modern society, important digital information that has a high business value and must be kept confidential (e.g., genome and medical information) has been and will continue to be generated in line with the evolution of computing technologies, AI, surveillance cameras, sensing technologies, and medical technologies as well as other technological developments. If data generated through the secondary use of this digital information leaks, the lives and lifestyles of victims from many families and generations are highly likely to be perpetually threatened. If actual damage occurs, the litigation risk and resultant compensation payouts could be astronomical, so we need to ensure confidentiality and tampering resistance (integrity) for centuries to come.

Furthermore, it is said that a quantum computer capable of decrypting public key cryptography methods (RSA cryptography and elliptic curve cryptography), which currently support the security of the Internet, could appear by around 2030. To counteract this, every country in the world is preparing to migrate to a new public key cryptography method (quantum-safe public key cryptography) that is expected to prove difficult to decrypt even if quantum computers are used. However, there is still a threat that even quantum-safe public key cryptography cannot protect against: an attack known as "Store Now, Decrypt Later," which involves attackers intercepting and storing encrypted data that cannot yet be decrypted with the aim of retroactively decrypting all of the data once a sufficiently advanced computer is developed in the future. Intelligence agencies in major countries are said to be using this method already. To protect against this threat, we need to develop a method of proving that no computer would be able to decrypt the encryption (information-theoretic safety).

In this R&D program, we aim to develop new technologies to continue to ensure the ultra-long-term security of cyberspace, which supports Society 5.0, and to realize the secure distribution, storage, and use of data protected against cyber security threats going forward and pursue the social implementation of such systems. We will start the social implementation of these systems by identifying potential users in fields that involve the handling of advanced secret information, such as the field of medical information and the field of critical infrastructure for enterprises, nations, and other organizations. We will also work on the application of these systems in the smart manufacturing field by working closely with the laser processing and photonic and electronic information processing teams involved in the SIP.

(i) Quantum cryptography technology

Lead researcher: FUJIWARA Mikio (Research Manager, Quantum ICT Advanced Development Center, Advanced ICT Research Institute, National Institute of Information and Communications Technology)

Participating organizations: National Institute of Information and Communications Technology, NEC Corporation, Toshiba Corporation, Gakushuin University, Hokkaido University, University of Tokyo, and ZenmuTech, Inc.

Summary of R&D:

Quantum cryptography is the only existing type of cryptography communication technology that can prove that not even someone who has access to unlimited computing power would be able to decrypt the encryption, and there are high expectations for its use as a means of protecting the communication of important digital information. However, quantum cryptography poses some challenges because, for example, it is more expensive than existing cryptography technologies, the market competitiveness of cryptography equipment is not very high, and the establishment of recommended standards is ongoing. In addition, quantum cryptography guarantees secure data communication, but it cannot guarantee secure data storage. In light of this, we will combine quantum cryptography technologies and secret sharing methods, which are conventionally used as a means of securely storing important digital information, while also working on the development of equipment that offers market competitiveness and standardization with the aim of realizing data storage that will, in theory, continue to completely prevent the leakage of secrets going forward.

Specific research details:

A) Quantum cryptography technology

Quantum cryptography can be broken down into the following two protocols depending on the type of detector that is used: BB84*1 and CV-QKD*2. In this R&D program, we use both of these methods.

At present, BB84 equipment is manufactured by procuring some of the parts from overseas. Given this, we will develop quantum cryptography equipment that offers market competitiveness by, for example, consolidating parts, modularization, softening, and the use of commercialized products, and maintaining the high key distribution performance with the aim of manufacturing all of the parts and equipment in Japan.

In R&D involving the use of CV-QKD, we will complete a research prototype by transferring CV-QKD technologies to companies through collaborations between universities and companies, improving the noise tolerance and light multiplicity, and further developing technologies to ensure that they can be operated stably and reliably in user environments.

In addition, we will conduct R&D into the following challenges posed by both methods.

i) Standardization of safety assurance technologies

To guarantee the information-theoretic safety of quantum cryptography in a production environment, we will repeat a cycle of basic theory, experiment, action implementation, and verification and then implement tamper resistance measures and side-channel attack prevention measures. We will reliably complete these activities, continue to advance safety assurance technologies, and sequentially standardize them.

ii) Size reduction of physical random generators

We will accelerate the speed of physical random generators, which play the central role in generating the keys for quantum cryptography, and halve the volume that these generators occupy in quantum cryptography equipment compared to conventional ones.

iii) Establishment of test criteria and a recommended method list

Test criteria and a recommended method list must be established to ensure that manufacturers manufacture and sell appropriate physical random generators and quantum cryptography equipment and that the users can use them safely. Because Japan does not yet have such a framework, we will conduct a feasibility study on its future operation, accumulate the basic data necessary for its operation, and draft a design for a system that will function as an ecosystem.

*1 BB84

This is a typical quantum cryptography protocol that uses a single-photon detector to detect particles of light (i.e., photons). It has been proven that this type of encryption cannot be decrypted using any form of wiretapping attack that is permitted by the laws of physics or by any computer with computing capabilities. The majority of R&D has long been focused on this protocol and companies are currently operating it as a trial. This protocol assumes a high-end usage, such as that required in the national security field, where the possibility of wiretapping must be eliminated completely.

*2 CV-QKD
This is a quantum cryptography protocol that uses a homodyne detector, which detects the phase and amplitude of light. A method of attacking communication channels by using this type of cryptography is limited to the physical operation of some classes. However even if the attack method is attempted, it is next to impossible to do so using current technologies. It has also been proven that this type of cryptography cannot be decrypted using any computer with computing capabilities. One advantage of this protocol is that it can be run alongside other protocols in fiber optics for optical communication. Consequently, it is expected that this protocol will be applied in the existing optical communication infrastructure. CV-QKD is less costly to develop than BB84, so it mainly assumes commercial high-end usage.

B) Quantum secure cloud technology

To realize a quantum secure cloud function, we will integrate the following: a secret sharing technology; a physical random generator and quantum cryptography technology; an electronic signature and authentication technology; and a secure computation technology. At this time, it will be essential for action to be taken to respond to an explosive increase in the amount of processing required and ensure the irreversibility of the encryption key to realize a quantum secure cloud function. To satisfy these needs, we will develop an optimal middleware application interface to integrate high-speed secret sharing and secure computation technologies with a light computation workload and encryption key management for operations.

C) Social implementation

Based on the assumption that medical information storage networks and critical infrastructure networks for enterprises, nations, and other organizations are representative applications, we will realize the social implementation of these systems while working with potential users in these fields.

In particular, we will categorize and prioritize the information assets to be handled for each usage type according to criteria such as the confidentiality level, data size, and usage frequency and develop an application that allows the user to access the necessary data as needed and perform the necessary processing or data restoration. We will also develop a gateway function to convert data into a common data format for data storage so that different organizations can mutually view the data.

Research goals:

Figure 2-(2) shows the more specific R&D goals and implementation framework.

A) Quantum cryptography technology

Goals in FY2019

- Complete the primary design for BB84 quantum cryptography equipment that has tamper resistance, fewer components, and parts that cost half that of conventional ones and then start the primary prototyping.
- For CV-QKD equipment, complete the basic design for manufacturing a test model according to a clear definition of the requirements and demand criteria to complete a semi-product.
- Complete the requirements definition for a modulator from the viewpoints of the theory related to deviations from the ideal transmitter-receiver model and the requirements with respect to the device characteristics when verifying the method for evaluating the implementation safety of the BB84 method in actual machines.

Interim goals to achieve by FY2020 (TRL4)

- Complete the implementation of tamper resistance measures and side-channel attack prevention measures while maintaining the key distribution performance of existing BB84 equipment. In addition, complete the development, evaluation, and verification of a primary prototype that is smaller and less costly.
- Complete the examinations necessary for the transfer of CV-QKD from universities to companies and its realization as a semi-product to complete the primary prototyping.
- For safety assurance technologies, create and release technical documents on basic policies and establish a framework for having them continuously updated and revised by the Quantum Key Distribution Technology Promotion Committee under the domestic organization called the Quantum ICT Forum. In addition, propose work items and contribute recommendation drafts to international organizations, such as the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) and the European Telecommunications Standards Institute (ETSI).

• Accelerate the speed of physical random generators by 10 times compared to current models (generation speed of several Gbps).

Final goals to achieve by FY2022 (TRL7)

• With the aim of receiving orders from high-end users, develop BB84 equipment that costs one-fourth as much as conventional equipment, which is equivalent to the current high-end common key cryptography model, and complete reliability tests in a field environment.

• Complete the creation of CV-QKD semi-product equipment (research prototypes that can run in user environments) in companies.

• For safety assurance technologies, issue recommendations on the main work items, such as implementation safety evaluations and key management, from the Quantum Key Distribution Technology Promotion Committee under the Quantum ICT Forum or international standardization organizations, such as the ITU-T or ETSI.

• Accelerate the speed of physical random generators by 10 times (generation speed of several Gbps) and halve their size (in terms of the volume that they occupy in the quantum cryptography equipment) compared to existing models and then transfer the technology to companies.

• Formulate a system design proposal to create and continuously update the test criteria and a recommended method list to guarantee the safety of physical random generators and quantum cryptography technologies and then recommend them to the relevant agencies.

B) Quantum secure cloud technology
Goals in FY2019

• Enhance the functionality of the sharing storage system for electronic medical records subject to high-efficiency secret sharing over a quantum cryptography network with a 100-km range so that it can be used as a secure and highly efficient data exchange foundation for medical institutions.

• Demonstrate the principle of facilitating a mutual data reference among multiple hospitals that use different electronic medical record systems on the JGN test bed.

• Develop a sharing storage system at three bases (10-km range) in Sendai to realize a system that allows for the secure storage of genome analysis data and then complete a basic evaluation.

Interim goals to achieve by FY2020 (TRL5)

• Prototype technologies designed to increase the efficiency of secret sharing and secure computation as well as the middleware required to integrate them with safe management and the operation of encryption keys, implement these prototypes on the field test bed, and then complete an evaluation of their basic performance levels.

• Demonstrate a function for integrating and restoring necessary medical data (e.g., medication history) of about 1 MB per person within 30 seconds in the event of an emergency, such as a disaster, by using simulated data in the standard data storage format recommended for electronic medical records.

Final goals to achieve by FY2022 (TRL7)

• Implement middleware that integrates technologies for reducing the computation workload for secret sharing and secure computation with key management and operations in a program on the field test bed and realize high-speed secret sharing for several dozen gigabytes of simulated electronic medical record data (processing speed: a few MB/s). Provide a suite of developed middleware as open resources on the field test bed.

C) Social implementation

Goals in FY2019

• Design an application for standardized medical data using the key management technology, which is an underlying technology for the quantum secure cloud, and demonstrate the wide-area sharing backup storage of electronic medical records and other medical data as a prototype.

• Create a sharing backup system at four bases in the Kochi Health Sciences Center and JGN as a demonstration environment and develop a system that restores data at high speeds (1 MB of data within 30 seconds).

• Apply quantum cryptography to the transmission of personal data during biometric authentication and the like to contribute to enhanced security when biometric authentication is used.

• Store the data for the sports medical records used by the All Japan Taekwondo Association on the NICT's network test bed and implement the secure sharing backup for this data by using the quantum secure cloud technology. In addition, monitor access to the server on which the data is stored by means of a face authentication technology that has enhanced safety by using the quantum cryptography technology to demonstrate the secure transmission and storage of personal data.

Interim goals to achieve by FY2020 (TRL5)

• Complete the development and verification of the main application software in the medical information storage network field. Realize a backup function that maintains the ultra-long-term security of electronic medical records and other data. Complete the prototyping and evaluation of advanced computing technologies for the safe secondary use of medical information.

• Develop application software for the processing of actual data in the field of critical infrastructure for Kochi Health Sciences Center, conduct simulations, jointly verify this software with users, and start building a network in a user environment.

Final goals to achieve by FY2022 (TRL7)

• Incorporate the results of test operations conducted by users into the network at about three urban bases in the field of medical information storage networks and the field of critical infrastructure for enterprises, nations, and other organizations and then complete the development of a business model to increase the number of operation users.

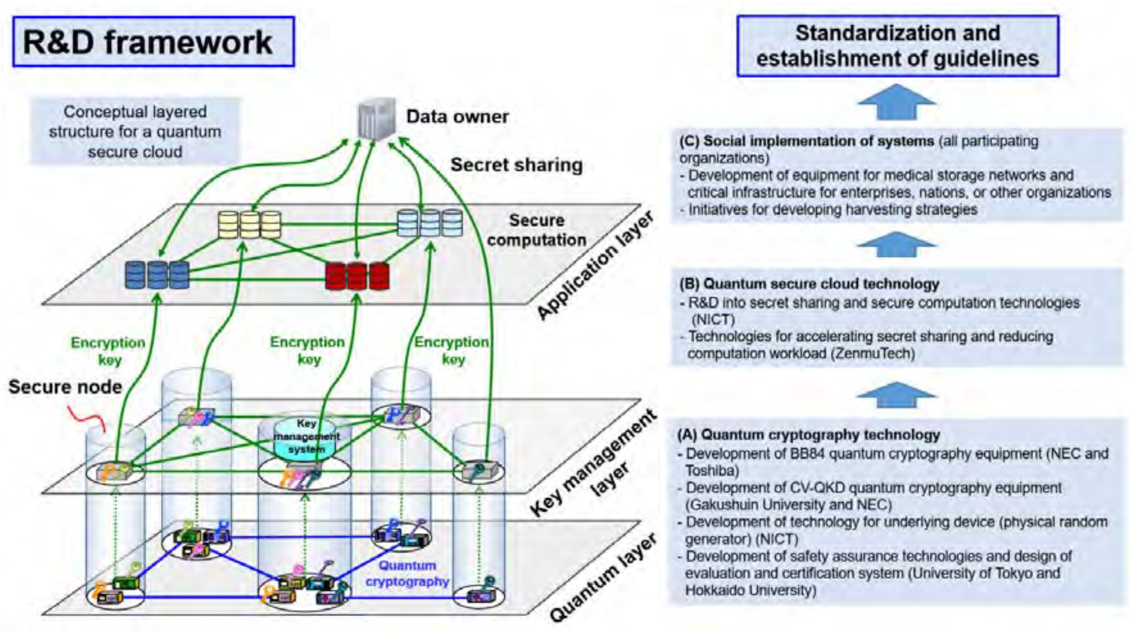

Figure 2-(2): Overview and implementation framework for R&D

Institutes and researchers for each R&D item:

(A) Item name: Quantum cryptography technology (National Institute of Information and Communications Technology [NICT], Toshiba Corporation, NEC Corporation, Gakushuin University, University of Tokyo, and Hokkaido University)

Task A1: Development of BB84 quantum cryptography equipment (IIZUKA Hiromi [NEC] and BABA Shinichi [Toshiba])

Task A2: Development of CV-QKD quantum cryptography equipment (HIRANO Takuya [Gakushuin University] and IIZUKA Hiromi [NEC])

Task A3: Development of technology for underlying device (physical random generator) (FUJIWARA Mikio [NICT])

Task A4: Development of safety assurance technologies and design of evaluation and certification system (KOASHI Masato [University of Tokyo] and TOMITA Akihisa [Hokkaido University])

(B) Item name: Quantum secure cloud technology (NICT and ZenmuTech, Inc.)

Task B1: R&D into secret sharing and secure computation technologies (FUJIWARA Mikio [NICT])

Task B2: Technologies for accelerating secret sharing and reducing computation workload (ISHIDA Yusuke [ZenmuTech])

(C) Item name: Social implementation of systems (NICT, Toshiba, NEC, Gakushuin University, University of Tokyo, Hokkaido University, and ZenmuTech)

Task C1: Development of equipment for medical storage networks and critical infrastructure for enterprises, nations, and other organizations (FUJIWARA Mikio [NICT], IIZUKA Hiromi [NEC], BABA Shinichi [Toshiba], HIRANO Takuya [Gakushuin University], KOASHI Masato [University of Tokyo], TOMITA Akihisa [Hokkaido University], and ISHIDA Yusuke [ZenmuTech])

Task C2: Initiatives for developing harvesting strategies (FUJIWARA Mikio [NICT], IIZUKA Hiromi [NEC], BABA Shinichi [Toshiba], HIRANO Takuya [Gakushuin University], KOASHI Masato [University of Tokyo], TOMITA Akihisa [Hokkaido University], and ISHIDA Yusuke [ZenmuTech])

(3) Photonic and electronic information processing

Deputy PD: The PD doubles as the deputy PD until the specific R&D is determined.

(i) R&D for a next-generation accelerator platform

Lead researcher: Applications open to the public.

Summary of R&D:

In Society 5.0, it is necessary to accumulate an enormous amount of physical-space data in cyberspace for a variety of industry fields (including smart manufacturing, the automobile industry, logistics, and materials), perform operations using this data instantaneously and flexibly, and then feed the results back in the physical space. Since artificial intelligence, which surpasses human abilities, analyzes an enormous amount of big data and then feeds back the results to human beings through robots or other machines, new types of value that would have been impossible until now will be created everywhere in industry and society.

Expectations for proposals and developments concerning the use of computers such as Ising computers (annealing-type quantum computers or Ising machines that utilize classic technologies), noisy intermediate-scale quantum (NISQ) computers, and fault-tolerant quantum computers as a mean of creating new value have increased, and Japan is also conducting comprehensive R&D into them across a variety of technologies. This is expected to significantly accelerate and advance processing and analysis in comparison with conventional computing methods by optimally leveraging these computing resources.

In this R&D program, we will widely position computers such as Ising computers (including quantum and classic computers), NISQ computers, and fault-tolerant quantum computers as computing accelerators and aim to build a system platform that can be leveraged by application program developers in application fields that contribute to Society 5.0. Furthermore, we will optimally leverage these computing resources to eliminate bottlenecks that impede the realization of Society 5.0.

For example, if we assume that computers such as Ising computers, NISQ computers, and fault-tolerant quantum computers are to be used as accelerators for individual computing resources, it is important to note that each accelerator may prove effective in some areas but ineffective in other areas. In addition, to leverage an accelerator, we need to prepare a data entry format that is optimal for the accelerator to be used (preprocess) and then retrieve and parse the output data (post-process). In this R&D program, we will accelerate and advance all of the application programs that contribute to Society 5.0, by attempting to use each of these accelerators in its appropriate place, to conduct R&D into a next-generation accelerator platform that will significantly accelerate and advance processing and analysis in comparison with conventional computing methods.

Specific research details:

1) Next-generation accelerator co-design technology

In Society 5.0, an enormous amount of data must be rapidly computed to a high degree of precision. To realize this level of computing, R&D is conducted into the use of computers such as Ising computers, NISQ computers, and fault-tolerant quantum computers as next-generation accelerators. Each of these types of computers is effective in some areas but ineffective in other areas. Furthermore, to leverage an accelerator, we need to execute an application program to prepare the data to be input into the accelerator, input the prepared data into the accelerator, retrieve the computing results after the accelerator has processed the data, and then continue to execute the original application program based on the retrieved results. The success of an accelerator depends on not only its processing time, but also a series of processes that include the preparation of the data to be input into the accelerator, the inputting of the data, and the retrieval and parsing of the output data. In addition, it may be necessary to prepare and input data as well as retrieve and parse the output data multiple times, changing the parameters and conditions as necessary, to achieve the optimal output results.

To accelerate and advance the application program as a whole, it is critical that we consider which type of acceleration is suitable for which part of the program and what should be actually used as the accelerator and that we optimize the application program and accelerator at the same time, assuming the use of classic accelerators, such as GPU, as well as Ising computers, NISQ computers, and fault-tolerant quantum computers (next-generation accelerator co-design). Given the above, we will formulate the next-generation accelerator co-design problem as a base technology for next-generation accelerators in this R&D program and conduct R&D into the system to find an optimal solution to this problem.

More specifically, we will work on the following R&D items.

i) Formulation of the next-generation accelerator co-design problem

Formulate the next-generation accelerator co-design problem based on the assumption that application programs that contribute to Society 5.0 will be accelerated and advanced using a variety of next-generation accelerators. Assuming the use of next-generation accelerators, we will need to abstract the application program architecture and optimize the processing speed and computing costs.

ii) Resolution of the next-generation accelerator co-design problem

Conduct R&D into the system to resolve the formulated next-generation accelerator co-design problem. Include a mechanism for calling each type of next-generation accelerator, receiving the results in the application program, and accelerating and advancing the application program as a whole.

2) Next-generation accelerator interface technology

Create an interface with the application program for each type of accelerator, such as an NISQ computer, a quantum computer, or a classic accelerator that uses a GPU.

Define the target problems for each type of accelerator, the input and output formats, and other such details in line with Task 1).

Social implementation:

Assuming the use of certain applications from smart manufacturing, logistics, materials, energy, the environmental industry, and other such fields as typical applications, realize the social implementation of systems by working with potential users in these fields on the retrieval and formulation of social problems and the selection and development of optimal solutions. After the SIP has been completed, we will realize the social implementation of these systems for each type of smart manufacturing application, such as image recognition processing and manufacturing equipment optimization, logistic services, new material searches, and the energy field (e.g., smart grid).

Development goals:

Interim goals to achieve by FY2020

- Complete the formulation of problems for the next-generation accelerator co-design base (TRL3).
- Complete the prototype design for the application program and the accelerator interface for each type of accelerator (TRL3).

Final goals to achieve by FY2022

- Complete the implementation of software to realize the next-generation accelerator co-design base and complete its adoption as an open test bed (TRL7).
- Accelerate the speed of typical applications by 10 to 100 times compared to conventional technologies that only use classic accelerators by using the next-generation accelerator platform and complete semi-product equipment in companies (TRL7).

3. Implementation framework

(1) Use of the National Institutes for Quantum and Radiological Science and Technology

We will conduct this SIP according to the framework shown in Figure 3-1 by using the operation subsidy granted to the National Institutes for Quantum and Radiological Science and Technology (QST). The QST will assist the PD and the Promoting Committee, publicly seek a lead researcher, conclude the necessary contracts, manage the finances and progress of the R&D, submit the self-inspection results to the PD and other related parties, and conduct related investigations and analysis among others.

(2) Selection of lead researcher

The QST selects a lead researcher through applications that are open to the public or other processes in accordance with this R&D plan.

The Public Offering Review Committee established in the QST after consultation with the Cabinet Office and other related parties determines the screening method, including screening criteria. Stakeholders including the lead researcher, joint researchers with whom the lead researcher plans to work, and subcontractors to which the lead researcher plans to consign work (re-consignment from the standpoint of the QST) as well as the PD and deputy PDs do not participate in the screening for the relevant lead researcher and other parties. The definition of stakeholders is as specified in the provisions and other regulations that the QST designates, but it can be changed as necessary after consultation with the PD, the Cabinet Office, and other related parties.

The QST determines the selection results with the approval of the PD and the Cabinet Office.

(3) Ways of optimizing the research framework

The PD supervises the deputy PDs assigned to each of the R&D items and determines the research framework through modifications, reshuffles, or additions related to the research programs and the lead researchers as well as other activities after discussions with each deputy PD.

A deputy PD capable of objectively seeing the big picture for the technologies in the relevant field and discussing matters with the lead researcher is assigned to each R&D item. The deputy PD manages the R&D and promotes research in each of the research programs as the person leading the R&D item for which he or she is responsible. In addition, the deputy PD examines the research subjects, research goals, necessary expenses, and research framework (including modifications, reshuffles, and additions) for the research program as well as the proposed harvesting strategies—including the implementation and integration of the results from other related projects in line with the progress made in the research program, the results of technology investigations or other research conducted by related organizations or other groups, and changes in the social conditions—proposes them to the management council, and obtains approval from the PD.

The Management Council is set up in the QST to help the PD make decisions. The Management Council determines the general policies for the R&D, sets the goals, manages the progress of the R&D, and examines proposals made by the deputy PDs with respect to matters such as the research subjects, the research goals, the necessary expenses for each research program, and modifications, reshuffles, or additions related to the research framework.

To continue monitoring changes in Japanese and international social and industrial trends and R&D trends in relation to laser processing (R&D Item 1) and photonic quantum communication (R&D Item 2) and to conduct R&D with optimal harvesting strategies, meetings of the relevant Subcommittee for the Review of the Harvesting Strategy are individually set up under the Management Council. Chaired by the deputy PD, these meetings are attended by the lead researcher, external experts, and other related parties.

(4) Cooperation between the Cabinet Office and Ministries

Under the R&D management of the PD and deputy PDs, the following bodies shall participate in the Management Council and subcommittees as observers: the Cabinet Office, the Ministry of Internal Affairs and Communication, the Ministry of Education, Culture, Sports, Science and Technology, and the Ministry of Economy, Trade and Industry. They shall also ascertain the progress made with respect to the research items and other such matters while closely cooperating with each other to ensure the social implementation of these research items by, for example, utilizing technologies developed under the related programs of the ministries in the SIP.

(5) Contributions from industry

Future contributions from industry (including personnel and material contributions) are expected to be 15 to 30% of the total R&D expenses (sum of the support provided by the Government and contributions from industry).

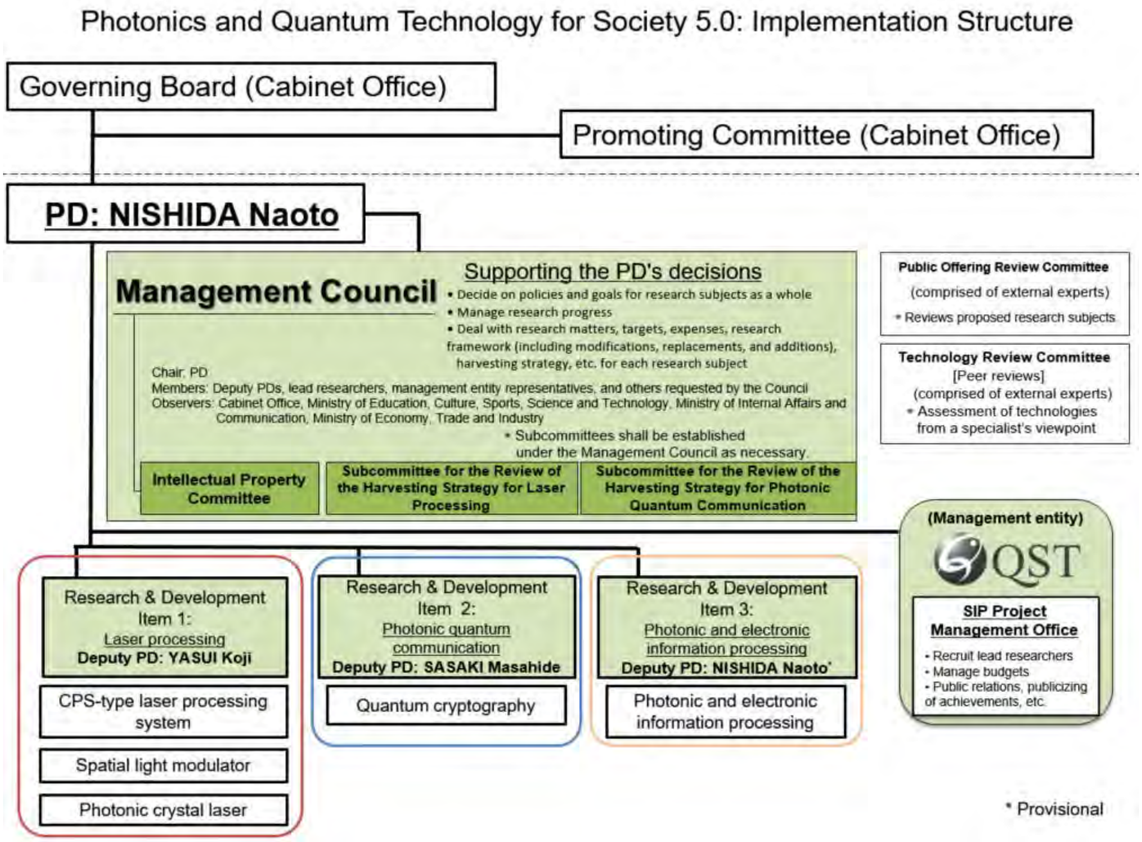

Figure 3-1 Implementation Structure

4. Matters related to Intellectual Properties

To ensure that Japan's national interests are served by making sure that this SIP is successful and then working to make the SIP achievements practically available and commercialize them, an incentive to encourage talented people and outstanding organizations to participate in the SIP will be secured and intellectual properties will be appropriately managed.

(1) Intellectual Property Committee

The Intellectual Property Committee shall be established under the QST. Additionally, in principle, an intellectual property subcommittee shall be established for each research subject in the institution to which the relevant lead researcher belongs.

The Intellectual Property Committee determines the policy for intellectual property rights (e.g., patents included in the outcomes of the research subjects as a whole and over multiple subjects) and undertakes coordination and arbitration for issues related to intellectual property rights that have not been settled by the intellectual property subcommittees. Each intellectual property subcommittee determines and coordinates the policy for the publication of papers on research achievements, the filing or maintenance of applications for intellectual properties rights (e.g., patents), and the like.

The Intellectual Property Committee is composed of the PD, deputy PDs, lead researchers, and management entity representatives as well as key related parties, experts, and others.

The detailed operation methods and rules for the Intellectual Property Committee and the intellectual property subcommittees shall be decided upon by the relevant institution to which they belong.

(2) Agreement on intellectual property rights

By entering into contracts and other agreements with trustees, the QST shall determine in advance matters concerning the handling of nondisclosure agreements, background intellectual property rights (intellectual property rights acquired by lead researchers or their institutions before participating in the SIP as well as those acquired by such parties without having used the SIP expenses after participating in the SIP), and foreground intellectual property rights (intellectual property rights generated during the SIP at the SIP's cost).

(3) Licensing of background intellectual property rights

With respect to the granting of licenses for background intellectual property rights to participants in other programs, the owners of the intellectual property rights may grant licenses in compliance with the conditions determined by the owners (or in compliance with an agreement entered into by the SIP participants).

If the actions of the intellectual property rights owners, including the licensing conditions, may hinder the promotion of the SIP (including not only the R&D but also the practical use and commercialization of the outcomes), the Intellectual Property Committee shall coordinate matters to reach a reasonable solution.

(4) Handing of foreground intellectual property rights

Article 19-1 of the Industrial Technology Enhancement Act (Act No. 44, 2000), in principle, applies to the foreground intellectual property rights, and the institutions (or the trustees) to which the inventors or the lead researchers belong shall have the ownership of these rights.

If a re-trustee or a similar entity creates an invention and the intellectual property rights revert to said re-trustee or entity, the Intellectual Property Committee's approval is required. In such case, the Intellectual Property Committee can add some conditions.

If the intellectual property rights owners do not intend to commercialize the properties, the Intellectual Property Committee recommends that ownership of the rights be transferred to people who actively intend to commercialize or grant licenses to them.

For participants who withdraw from the SIP before the end of the term, the QST can transfer all or part of the achievements that they have made during their participation at the SIP's cost (all of the achievements since their first participation if they have participated in the SIP for multiple years) to QST for free and QST can grant licenses for the transferred achievements to them at the time of their withdrawal.

In principle, the expenses incurred in applying for and maintaining intellectual property rights shall be shouldered by the intellectual property rights owners. For cases involving joint applications, the ratios for the ownership share and expense quota shall be determined through discussions between the joint applicants.

(5) Licensing of foreground intellectual property rights

With respect to the granting of licenses for foreground intellectual property rights to participants in other programs, the owners of the intellectual property rights may grant licenses in compliance with the conditions determined by the owners (or in compliance with an agreement entered into by the SIP participants).

With respect to the granting of licenses for foreground intellectual property rights to third parties, the owners of the intellectual property rights may grant licenses in compliance with the conditions determined by the owners as long as said third parties shall not enjoy more favorable conditions than those for the SIP participants.

If the actions of the intellectual property rights owners, including the licensing conditions, may hinder the promotion of the SIP (including not only the R&D but also the practical use and commercialization of the outcomes), the Intellectual Property Committee shall coordinate matters to reach a reasonable solution.

(6) Approval of the transfer of foreground intellectual property rights and the establishment or transfer of exclusive licenses

Based on Article 19-1-4 of the Industrial Technology Enhancement Act (Act No. 44, 2000), the transfer of foreground intellectual property rights and the establishment or transfer of exclusive licenses shall be conducted only after the QST's approval has been obtained, except for in cases involving the transfer of rights due to the splitting or merging of participating organizations, the transfer of intellectual property rights, or the transfer or establishment of exclusive licenses to subsidiaries or the parent company (hereafter referred to as "cases involving the transfer of intellectual property rights or similar actions due to a merger or similar changes").

In cases involving the transfer of intellectual property rights or similar actions due to a merger or similar changes, the intellectual property rights owner must obtain the QST's approval based on its contract with the QST.

Even after the transfer of intellectual property rights or similar actions due to a merger or similar changes, the QST can retain the license with sublicense rights. If this condition is rejected, the QST will not approve the transfer.

(7) Handling of intellectual property rights at the end of the SIP

The Intellectual Property Committee holds discussions on how to handle (abandonment or succession by the QST) intellectual property rights that nobody wants to own at the end of the R&D program.

(8) Participation of overseas institutions or people (e.g., foreign companies, universities, or researchers)

If the participation of foreign institutions or people is needed for certain research subjects, such parties can participate in the SIP.

From the viewpoint of administration, such participants must have representatives in Japan, in principle, to deal with the paperwork for contracts related to the research.

Intellectual property rights that involve a foreign entity shall be owned jointly by the QST and the relevant foreign entity.

5. Assessment Items

(1) Subject of assessment

The Governing Board assesses the SIP together with invited external experts and professionals with reference to the self-inspection results of the PD, the QST, and other groups and the QST's peer review results. The Governing Board can hold assessment meetings separately by research field or subject.

(2) Time of assessment

Three types of assessment shall be made: prior assessments, annual fiscal year-end assessments, and final assessments.

When a specified period (three years in principle) has passed since the final assessment, a follow-up assessment shall be conducted as necessary.

In addition to the assessments described above, assessments can be conduct in the middle of a fiscal year as well if necessary.

(3) Assessment items and assessment standards

Based on the General Guidelines for the Assessment of Government-Commissioned Research and Development (determined by the then Prime Minister on December 21, 2016), the assessment items and assessment standards are as described below from the viewpoint of assessing values such as necessity, efficiency, and effectiveness. The assessment process not only judges whether the targets are achieved or not, but also analyzes the relevant causes or factors and proposes improvements and other measures.

(i) Importance of this SIP's significance and its consistency with the Cabinet Office's purposes for SIPs.

(ii) Validity of the targets (outcome targets in particular) and progress made in relation to the process chart toward achievement.

(iii) Appropriate management as well as effectiveness of cooperation between the Cabinet Office and Ministries.

(iv) Strategy and achievement level in relation to practical use and commercialization.

(v) Expected effects or ripple effects at the final assessment as well as clear and appropriate follow-up methods after the end of the final assessment.

(4) Utilization of the assessment results

The prior assessment is conducted on the plans and other matters for the next fiscal year onward, and the results of this assessment are then fed back into the plans.

The fiscal year-end assessment is conducted on the achievements that have been made up to the present fiscal year and the plans or other matters for the next fiscal year onward, and the results of this assessment are then fed back into the plans or other matters for the next fiscal year onward.

The final assessment is conducted on the achievements that have been made up to the final fiscal year, and the results of this assessment are then fed back into the follow-up assessment carried out after the end of the final assessment.

The follow-up assessment is conducted on the progress that has been made in relation to the practical use and commercialization of the research outcomes, after which improvements and other measures are proposed.

(5) Disclosure of the results

In principle, the assessment results shall be released.

The results of assessments conducted by the Governing Board are not released, because they also deal with non-disclosure R&D information.

(6) Self-inspections

(i) Self-inspections by lead researchers

The PD shall instruct the lead researchers to conduct self-inspections.

Referring to the assessment items and standards described in section 5-(3), the lead researchers shall conduct inspections on the achievements made since the previous assessment and the future plans. After that, they shall not only judge whether the targets are achieved or not, but also analyze the relevant causes or factors and then put together improvements and other measures.

(ii) Self-inspections by the PD

Looking into the lead researchers' self-inspection results and referring to the assessment items and standards described in section 5-(3), the PD shall conduct his/her own self-inspection and assess the achievements of the QST and each lead researcher and the future plans. After that, the PD shall not only judge whether the targets are achieved or not, but also analyze the relevant causes or factors and then put together improvements and other measures. Based on the results, the PD shall decide whether each lead researcher should continue his/her research activity and issue appropriate advice to the lead researchers and other members. In doing this, the PD can help the organization to improve itself autonomously.

Based on these results, the PD shall create documents to be submitted to the Governing Board with the support of the QST.

(iii) Self-inspections by the QST

The self-inspections of the QST are conducted to determine whether the QST is implementing office processes for the use of budgets appropriately.

(7) Peer review

To conduct technological assessments from a specialist's viewpoint (hereafter referred to as a "peer review"), the QST has established the Technology Review Committee and research subject subcommittees, which are composed of external experts confirmed by the Cabinet Office, to develop an organization that is capable of conducting peer reviews with a higher degree of specialty. This organization will be strengthened so that it is able to implement global and objective assessments, including assessments of harvesting strategies aimed at social implementation, such as incorporating the viewpoints of world-leading application-oriented overseas research institutions in the Technology Review Committee. Additionally, to ensure that appropriate peer reviews are conducted, the opportunities for discussions will be increased so that the Technology Review Committee, the PD, deputy PDs, and lead researchers can hold in-depth discussions. The QST shall compile the peer review results from the Technology Review Committee and report them to the Governing Board.

Our technologies in the selected three fields already hold world-class technological advantages. However, it is important to determine if the social implementation strategy for this SIP meets the social trends and the market demands from a global viewpoint and then use the review results as feedback for the strategy. For this reason, in FY2019, this SIP will use leading overseas investigation and research institutions to conduct investigations of technological trends in the photonic and quantum field and then promote active discussions based on global viewpoints in the peer review.

6. Harvesting Strategy

Leveraging Japan's advantages in photonic and quantum technologies, this SIP will conduct R&D into the technological fields of laser processing, photonic quantum communication, and photonic and electronic information processing and then promote investment by private companies to secure and improve Japan's industrial competitiveness by realizing smart manufacturing, smart mobility (automated driving), and smart energy.

(1) Harvest-oriented research

(i) Using business networks and establishing links with them

To expand R&D outcomes widely throughout the market, it is essential to obtain favorable reviews of market-dominant companies in the early stages. This SIP will disclose as much information about its R&D achievements as possible to Japanese and international business networks (e.g., in the electronic equipment field), allow each company to hold discussions on their practical use and then, by reviewing some specific evaluation and utilization examples, decide whether the social implementation of these achievements has any feasible practical uses as early as possible to feed the results back into the R&D activities. For example, by operating the Meister laser processing system and the smart laser processing system to be established through R&D into CPS-type laser processing systems as the intelligence center for smart manufacturing, this SIP will conduct various actions, such as collecting information on needs, collecting technological data by conducting test processing, obtaining feedback on processing evaluations, conducting outreach work, and establishing partnerships. Adopting this approach will help to prepare an environment in which many stakeholders can use the systems and improve the system performance.

In a study conducted by utilizing meetings held by the relevant Subcommittee for the Review of the Harvesting Strategy and other such bodies to determine the best options for the social implementation of the achievements, inviting or establishing venture businesses will be studied as one of the options. In addition, the PD, deputy PDs, lead researchers, and other members will obtain accurate information on overseas leading institutions with the aim of learning about overseas examples of advanced social implementation and understanding the overseas situation more correctly.

(ii) Links to related programs

- With respect to R&D into CPS-type laser processing systems, the SIP will accelerate the development process by cooperating on the outcomes of other national projects, such as a project initiated by MEXT called Q-LEAP and a project initiated by METI and NEDO called the Development of Advanced Laser Processing with Intelligence Based on High-Brightness and High-

Efficiency Next-Generation Laser Technologies, in this SIP.

• By combining the ultra-long-term secure secret sharing storage technology of the Cabinet Office's ImPACT program called Advanced Information Society Infrastructure Linking Quantum Artificial Brains in Quantum Network together with a secure computation technology and other related techniques for quantum cryptography, this SIP will realize a quantum secure cloud technology. In addition, advanced core techniques for securing ultra-long-term security will be provided to other projects for the second term SIP with the aim of spreading this technology.

• For photonic and electronic information processing, the SIP will accelerate the development process by avoiding any overlap with the activities involved in the Cabinet Office's ImPACT, MEXT's Q-LEAP, a project initiated by METI and NEDO called the Project for Innovative AI Chips and Next-Generation Computing Technology Development, and other such projects and combining the outcomes of these other projects with this technological research where appropriate.

(iii) Areas of the SIP activities and entities to which the development outcomes are to be transferred

• Although different research items have different technological maturity levels depending on their foundation technologies and development progress, the overall aim is for one or two of them to reach TRL7.

• Companies that participate in the research subjects and those who are licensed to use the intellectual properties will translate the research outcomes into the market as products or services. Refer to the attached process chart for specific harvesting strategies that utilize the research outcomes.

(iv) Contributions of personnel, materials, and funds from participating companies

• Participating companies shall contribute to the promotion of R&D activities by providing personnel, equipment, and technological knowledge. As the prospects for the commercialization of the R&D outcomes become clearer, these companies shall also contribute funds for these activities with the aim of launching products. Refer to the attached process chart for specific fund plans.

(2) Measures for promoting the research outcomes

To promote and spread the research outcomes, this SIP will not only use the business networks described earlier, but also utilize existing entities, such as private companies and venture businesses (startup companies generated by universities and research institutions), as resources of social implementation on a business basis, including small and medium companies. For CPS-type laser processing systems in particular, associations such as linked businesses and related consortiums will be used to promote these systems.

In addition, this SIP will also conduct active and strategic advertisement activities for the research outcomes, promote the permeation of research outcomes into Japanese and overseas companies and institutions, and expand the global share of those businesses to make them flagships in related industries. In particular, this SIP will hold high-impact events, such as demonstrations using actual devices, for not only related companies but also the general public and press communities to conduct activities that will help actively expose the research outcomes to the mass media. For this purpose, the Management Entity hired some full-time personnel to enhance the advertisement performance (promotion) starting from this fiscal year.

7. Other Important Items

(1) Related laws and regulations

This SIP is implemented based on the following laws and guidelines: Article 4, Paragraph 3-7-3 of the Act for Establishment of the Cabinet Office (Act No. 89 of 1999), the Basic Policy on the Utilization of Funds for the Promotion of Scientific and Technological Innovation (Council for Science, Technology and Innovation, May 23, 2014), the Implementation Policy for the Second Term (allocation of the supplementary budget for FY2017) of the Strategic Innovation Promotion Program (SIP) (Council for Science, Technology and Innovation, March 29, 2018), and the guideline of the Strategic Innovation Promotion Program (SIP) (Governing Board of Council for Science, Technology and Innovation, May 23, 2014).

(2) Flexible plan revisions

This SIP can be reviewed flexibly from the viewpoint of gaining the most significant outcomes as quickly as possible.

Instead of setting the SIP periods uniformly to five years for all of the research subjects, the research subjects will be set up flexibly by, for example, adding subjects for new needs at the time of their occurrence based on the achievements of other related projects.

(3) Personal histories of the PD and the councilors in charge

(i) PD

NISHIDA Naoto (since June 2018)

(ii) Councilors in charge (directors)

CHISHIMA Hiroshi (April to October 2018)

NISHIYAMA Takashi (April to October 2018)

TONOUCHI Toshio (since October 2018)

OKU Atsushi (since October 2018)

(iii) Officer in charge

RYU Masahiko (since April 2018)

Attachment 1: Fund plan and estimate

Fiscal 2018: 2,500 million yen in total

<u>Breakdown statement</u>

1. Research expenses, etc. (including general management and indirect expenses)

2,360 million yen

Breakdown by research item:

(1) Laser processing	1,940 million yen
(2) Photonic quantum communication	419 million yen
(3) Photonic and electronic information processing	1 million yen

2. Project promotion expenses (e.g., labor, evaluation, and meeting expenses) **140 million yen**

Total **2,500 million yen**

Fiscal 2019: 2,280 million yen in total

<u>Breakdown statement</u>

1. Research expenses, etc. (including general management and indirect expenses)

2,100 million yen

Breakdown by research item:

(1) Laser processing	1,291 million yen
(2) Photonic quantum communication	559 million yen
(3) Photonic and electronic information processing	250 million yen

2. Project promotion expenses (e.g., labor, evaluation, and meeting expenses) **180 million yen**

Total **2,280 million yen**

Attachment 2: TRL definition in this SIP

TRL #	Definition
TRL1	Basic principles observed and reported
TRL2	Technology concept and/or application formulated
TRL3	Analytical and experimental critical function and/or characteristic proof of concept
TRL4	Component and/or breadboard validation in laboratory environment
TRL5	Component and/or breadboard validation in relevant environment
TRL6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL7	System prototype demonstration in a space environment
TRL8	Actual system completed and "flight qualified" through test and demonstration (ground or space)
TRL9	Actual system "flight proven" through successful mission operations

Projects under this SIP shall conform to the TRL definition of NASA listed in the above table.