Interim Report for the Promotion of Photon Science and Technology

— Way to Promote Measures for Photon Science and Technology in the Future —

July 2007

Special Task Force on Promotion of Photon Science and Technology

Executive Summary

○ Photon science and technology (S&T) itself is the subject of important basic science, including quantum mechanics and electromagnetics, etc. It is also a key technology that leads important research and development in the fields of life science, nanotechnology/materials, environment and information & communications, and is thus the source of innovation. From this viewpoint, China, not to mention the United States and European countries, are making active efforts through industry-academia-government cooperation.

○ Special Task Force on Promotion of Photon Science and Technology (Chairperson: Yoshiaki KATO, Director, Quantum Beam Science Directorate, Japan Atomic Energy Agency) was established in February 2007. In July 2007, the task force compiled an interim report concerning the way to promote measures for photon S&T in the future.

2. Key points of the report

○ In addition to the world's most advanced research results, which were obtained with the use of SPring-8, etc., there have been, so far, some elemental technologies unique to Japan that lead the world.

(Examples) Vertical-cavity surface-emitting laser (VCSEL) diode, photonic crystal, ceramic laser device, optical lattice clock, X-ray free electron laser (XFEL), etc.

○ Photon S&T have not been clearly positioned either as a scientific/academic area or as a priority S&T field that is to be strategically promoted. There are no intensive light source development projects, except for those in specific areas, such as SPring-8 and XFEL.
Networking among researchers and research institutes is insufficient. Collaboration/fusion between seeds in the field of photon S&T and needs in other fields is also insufficient.

○ To induce epoch-making innovation in each field and industry, it is necessary to develop new photon sources that generate light with unprecedented characteristics and to actively promote projects focusing on application research for such photon sources.

(Examples) Control of chemical reaction processes by means of laser beam, etc., small/low-cost cancer treatment equipment, noninvasive test of hidden materials, etc.

○ The Interim Report pointed out the importance of efforts to develop human resources that will lead the next-generation photon S&T by establishing networked research bases, in which seeds in the field of photon S&T and needs in other fields are combined, through promotion of new programs.

○ Even after completion of XFEL, investments of at least the same scale as now are necessary for the mean time.

Outline of the Interim Report

1. Necessity to Promote Research in Photon Science and Technology

○ The field of photon science and technology (S&T) is an important one that leads advanced S&T fields, and it is the source of innovation. Countries other than Japan are competing with each other to strategically promote research and development, in order to realize "new photon tools" in advance of others and utilize them through innovative methods.

○ It is important to establish composite/interdisciplinary photon S&T, which covers the fields of science and engineering, including photonics, electromagnetics, quantum mechanics and laser engineering, as a new scientific/academic area. It is also necessary to actively promote photon S&T by positioning it as a priority field that should be strategically promoted.

2. Trends of Research in Photon Science and Technology in Foreign Countries

<Points common to foreign countries>

○ Actively promoting specific measures for photon S&T while clearly positioning it as the most important basis of the priority S&T fields that are to be strategically promoted

○ Setting up several research bases in order to enable researchers in the field of photon S&T, equipment developers/manufacturers and strategic partners to promote research and development through organic collaboration and fusion with each other

3. Current Situation and Problems in Japan

(1) Current situation of research at universities and public research institutes, etc. and future issues

○ Other than large-scale research and development projects, such as application research for large-scale synchrotron radiation facilities (SPring-8, etc.) and development of XFEL, research in the field of photon S&T is being conducted in the Basic Research Programs, leading projects and ordinary research projects based on subsidies for operating expenses. Some world-leading research results have been obtained.

(Examples) VCSEL, photonic crystal, ceramic laser device, optical lattice clock, etc.

○ Photon S&T have not been clearly positioned either as a scientific/academic area or as a priority S&T field that is to be strategically promoted. Therefore, there are no active photon source development projects. Consequently, the following problems are pointed out.

× Networking among researchers and research institutes is insufficient.
× Not many research projects are conducted through collaboration/fusion between researchers in the field of photon S&T and those in other fields.
× Japanese researchers cannot conduct the world's best research as they have no choice but to depend on light sources made in the United States and European countries.
× A mechanism of systematic education/human resources development in the field of photon S&T has not been established.

(2) Current situation and problems in the industry

○ The Japanese optoelectronics industry maintains an extremely high production capacity for high-demand general-purpose products, such as low-power semiconductor laser, at present. However, it is reluctant to develop advanced equipment, such as a high-power semiconductor laser, which is expected to create new demand in the future.

4. Research in Advanced Photon Science and Technology

○ In order to induce the following epoch-making innovations in each field and industry, it is necessary to actively promote a variety of application research as well as develop new photon sources that are indispensable for research and development of these innovations (attosecond laser pulse, high-repetition rate petawatt laser pulse, coherent soft X-ray, far-infrared ray, light with a high frequency stability, light of which the phase is under control, high-efficiency/high-power semiconductor laser, etc.).

① Clarification and control of chemical reaction processes by means of laser beam
② Small/low-cost cancer treatment equipment, nondestructive imaging/nuclear waste management using high-intensity γ-ray, and fusion-based new energy source
③ Technology for detecting foreign substances (hazardous materials/tumors) by living cellular diagnosis or by clear transparent images without exposure
④ Processing technology using clean and energy-saving photon tools, which is applicable in various industrial fields
⑤ Undecipherable optical cryptography and ultrahigh-capacity/ultrahigh-speed optical information and communications technology
⑥ Cutting-edge nanomedicine and optoelectronics industry using new processes of crystal growth/nanoparticulation by means of laser beam, etc.

5. New Efforts to Promote Research in Photon Science and Technology

○ It is necessary to promote networking in order to organically combine seeds in the field of photon S&T and needs in other fields.

○ For this purpose, the Interim Report proposes measures based on two different programs.

<Program for new photon tools in public offering>

Establishing networked research bases, in which the industry and strategic partners, etc. participate, centering on several research institutes in the field of photon S&T, and carrying out human resources development and research and development of new light sources/measuring methods, etc.

<Program for application studies in public offering>

Promoting innovative research projects, which are conducted by strategic partners utilizing cutting-edge light sources, etc. in unprecedented ways, with strong support from photon source developers, etc.

○ A research promotion system is to be established to consistently promote both programs in a mutually complementary manner.

○ Even after completion of XFEL, investments of at least the same scale as now (about 50 billion yen annually for all of Japan) will be necessary for the meantime.

Contents

Introduction

"Enabling Technology" is a technology for solving very difficult problems in various fields. One example of enabling technology is the steam engine in the 19th century. It served as the driving force for the progress of the Industrial Revolution in the latter half of the 18th century. The 19th century can be called the "century of steam." In the 20th century, "electronics," represented by a transistor, served as an enabling technology and dramatically increased convenience to society. The 20th century came to be called the "century of electronics."

On the other hand, it has become possible to actively utilize many excellent features of the "photon" since laser was invented in 1960. Technologies utilizing the features of the "photon," such as large-capacity/high-speed optical communications, endoscopic diagnosis and photocatalysts, have spread to every corner of contemporary society. "Photon science and technology (S&T)" has such features as ultrahigh-speed, ultra-precision, contact-free characteristics and high energy concentration. It is regarded as a new enabling technology beyond any prior art, and relevant research and development have been promoted at a high speed on a global scale. The 21st century is becoming the "century of the photon."

In Japan, research and development of optical information and communications technology, research on laser fusion, construction of a large-scale synchrotron radiation facility, and development of an X-ray free-electron laser have been performed by measures such as the Basic Research Programs. The characteristic of photon S&T is that creative outcomes of basic research link directly to scientific and technological innovation as well as industrial innovation. Through research relating to photon S&T, many creative outcomes have been produced in Japan, including development of blue laser diode and photo-catalytic materials. However, these outcomes have not necessarily been sufficiently utilized for the progress of S&T as well as industry. Therefore, it is difficult to say that excellent research and development capability in Japan has been sufficiently exploited. In contrast with the United States and European countries where photon S&T are being rapidly promoted through an effective combination of investments by the state and the industry, Japan's delay in taking action has been of concern.

The Research Promotion Bureau of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) set up the "Special Task Force on Promotion of Photon Science and Technology" in February 2007, and has thereby promoted consideration of the establishment of a foundation for photon S&T in Japan. In particular, repeated discussions were held on the following: (1) independent development of advanced light sources and the exploitation of new fields of application through close collaboration with various fields in which photon S&T are used, (2) human resources development at universities and in the industry, and (3) the necessity of establishing photon science as a discipline. During these discussions, persons concerned visited research institutes in the United States and European countries to conduct detailed study on efforts for research and development in the fields of photon S&T in these countries.

This report is a summary of achievements of the said round-table conference, and it proposes various measures for fully working on the research and development of photon S&T in Japan. We hope that this report will contribute to the formulation and implementation of Japan's measures, such as the S&T Basic Plan and Innovation 25.

1. Necessity to Promote Research in Photon Science and Technology

"First let there be light" is now a common idea in cutting-edge researches as well as industrial scenes.

Progress in the four priority fields set in the S&T Basic Plan in our country, such as IT (information and telecommunications), nanotechnology/materials, life science, the environment and energy, cannot stand without advanced photon tools. Actually, since the laser was invented in the 1960s, a number of research in each field and related industries have dramatically improved. For example, micro measurement and fine processing using light with various features have become available. In addition, new optical technologies, such as broadband Internet and blue ray discs, have firmly made their way into our lives. In the scientific field, high-intensity synchrotron radiation can analyze the composition and formation of substances in detail. The advanced photon tools are leading research in cutting-edge fields, such as nanotechnology/materials and life science, and are serving as the driving force for the growth of these fields.

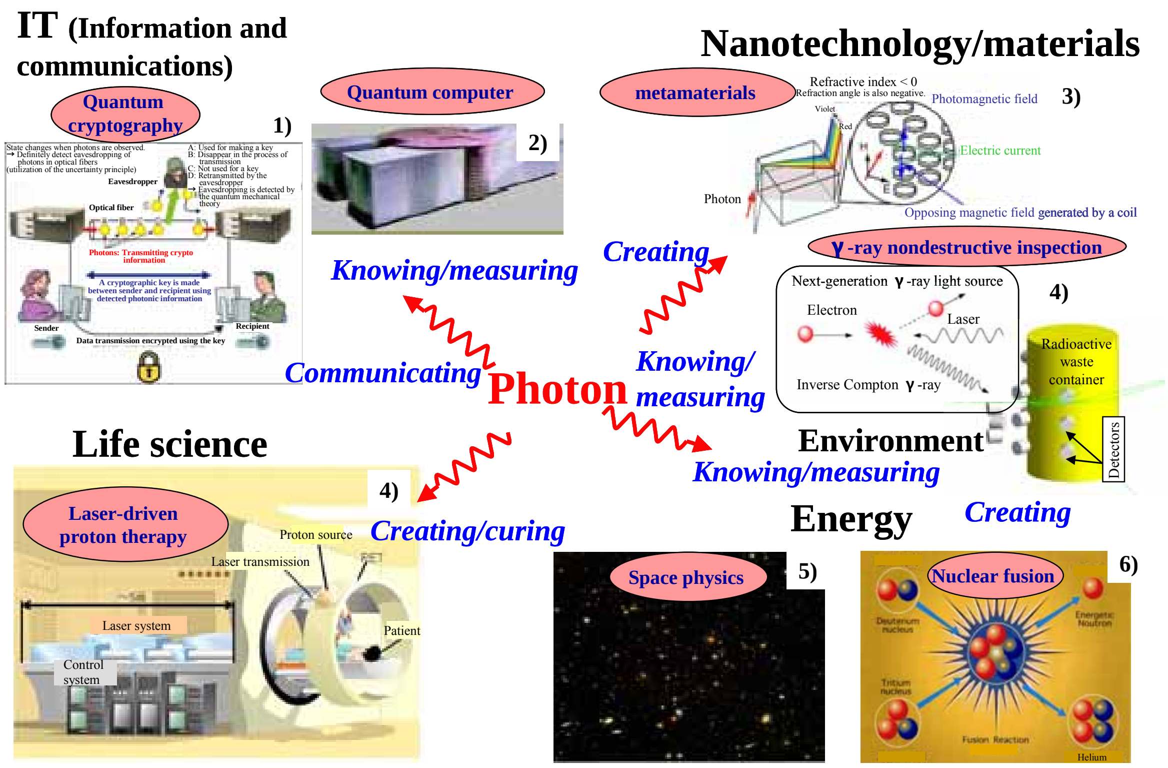
In this manner, photon S&T have widely spread from basic research to industrial fields, and they are positioned as indispensable technology for every field.

Light/photon tools mentioned here refer to electromagnetic waves in the wide wavelength range covering from terahertz light, which is close to an electronic wave, to X-ray and γ-ray, of course including visible light. In the light region, flexible controlling of light intensity and other basic characteristics, like electronic waves, was achieved in the latter half of the 20th century. For the fulfillment of further light control, new technology is desired to control pulse characteristics, coherence (identical motion/oscillation with the same waveform in the traveling waves), and polarization, etc. in the wide wavelength range. If such technology becomes available, that is, sophisticated photon tools, are obtained in more diversified wavelength ranges than ever before, they will stimulate the exploitation of epoch-making applications and the discovery of unknown phenomena depending on their potential. For example, X-ray free-electron laser (XFEL), now under construction, will make it possible to conduct epoch-making research activities since it enables clarification of complex phenomena within the X-ray region (nonlinear phenomenon, etc.). It also enables structural analysis of proteins without crystallization by means of the coherent X-ray light source which had not been available in the past. Moreover, advanced photon tools will be applicable to know the environmental pollution, birth of stars, and origin of the universe, and to create new materials and energy, and to transmit massive high-quality information in safety. Therefore, photon S&T is extremely important as a key innovative technology for carving out a new era. (see Figure 1).

Understanding the principle of "new photon tools," and clarifying the mechanism of interaction with matter fertilize basic sciences of material science, life science and space science, etc. Therefore, the field of photon S&T requires intensive promotion from a comprehensive viewpoint not only by using it as mere infrastructure or fundamental technology but also by establishing its basis through systematization as a new scientific/academic area.

On the other hand, it is important for the creation and revitalization of industries to verify the effectiveness of "new photon tools," which were realized in advance of others, through early use thereof and to lead them to the exploitation of new fields of application in the future of the optoelectronics industry. The United States and developed countries in Europe have already launched research focusing on "new photon tools" in the 21st century, which is called the "century of the photon," and are promoting research and development in fierce competition. Particularly, photon S&T is clearly positioned as the key technology of the National Nanotechnology Initiative (NNI) in the United States, while it is positioned as one of the pillars of 17 cutting-edge fields in the "High-Tech Strategy for Germany" in Germany. Thereby, these countries are actively promoting specific measures.

Japan is also required to actively promote research and development in advanced photon S&T based on "new photon tools," as the priority field. Now is an extremely important time.



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4) "HIKARI Center," Kansai Photon Science Institute, Japan Atomic Energy Agency
5) http://upload.wikimedia.org/wikipedia/commons/2/2f/Hubble_ultra_ deep_field.jpg
6) http://www.ile.osaka-u.ac.jp/zone3/explanation/what/index.html

Figure 1. Examples of cutting-edge science by new photon tools

2. Trends of Research in Photon Science and Technology in Foreign Countries

If a “new photon tool” with an unprecedented feature can be built faster than others, that unique tool would provide innovative methods in photon science as well as other priority fields. As a result, we can get the opportunity to obtain the top of the world position in these fields. Therefore, China and South Korea, as well as the United States and European countries, have been competing to promote research and development in the field of photon S&T. Points common to these countries are listed below.

◎ The government is actively promoting specific measures for photon S&T while clearly positioning it as the most important basis of the priority S&T fields that are strategically promoted.

— In the United States, photon S&T is clearly specified as an important sub-theme in various programs. For example, it is cited as the key technology of the National Nanotechnology Initiative (NNI). The U.S. government is strongly promoting photon S&T based on specific measures.

— In Germany, photon S&T is clearly positioned as one of the pillars of 17 cutting-edge fields of great promise, which should receive strategic investment, in a basic S&T policy titled “High-Tech Strategy for Germany” (started in 2006).

◎ Several research bases have been set up in order to enable researchers in the field of photon S&T, equipment developers/manufacturers, and strategic partners to cooperate to conduct research and development using "new photon tools."

◎ Researchers and engineers in various fields have been promoting research through organic collaboration and fusion. Regarding large research facilities, strategic partners are proposing ideas on the specifications of devices from the design phase toward future use.

◎ Since the industry also cooperates in carrying out development of such tools as advanced light sources and measuring equipment, technologies are smoothly transferred to the industry.

(1) United States

In the United States, there has been no policy specialized toward photon-related S&T. However, photon S&T has been clearly specified as an important sub-theme in various programs. For example, it was cited as the key technology of the National Nanotechnology Initiative (NII). Thereby, the government is strongly promoting photon S&T based on specific measures.

In addition, the Department of Energy (DOE) establishes and operates the large research facilities, including the National Ignition Facility (NIF). With respect to research aid, the DOE and the National Science Foundation (NSF) conduct at universities and public research institutes, while the National Institute of Standards and Technology (NIST) of the Department of Commerce provides support for practical application of technology development by private companies.

Other than these, there are several educational research institutes that promote photon S&T from the perspectives of both research and education. These institutes serve as sources of innovation.

- Institute of Optics at the University of Rochester
- College of Optical Sciences (former Optical Sciences Center) at the University of Arizona
- "Townes Laser Institute" at the College of Optics and Photonics at the University of Central Florida, etc.

The following are cited as the research and development fields relating to photon S&T to which the United States pays special attention: ultrafast phenomena, terahertz science, measurement of functions of membrane proteins, metamaterials, organic EL, ceramic laser, pulsed X-ray imaging, generation of inverse Compton γ-ray, photophysics in the X-ray region, and strong photon field science.

(2) Europe (the EU, the United Kingdom, France and Germany)

① EU (European Union)

Under the Seventh Research Framework Programme (FP7; 2007−2015; Total budget: 50.5 billion euros), photon S&T are clearly specified in one of the subprograms, nanoscience/nanotechnology. Photon S&T has been strategically promoted in consideration of energy strategy in the future. Although the ESFRI (European Strategy Forum on Research Infrastructures) is formulating research plans for the next 10 to 20 years, programs to promote research in photon S&T account for five out of 35 programs (budget: 3 billion euros), as shown below.

- HiPER (High-power long-pulse laser for fast-ignition fusion, 0.85 billion euros): Development of a light source for laser fusion, designed to be launched eight years later
- ELI (Extreme light intensity short-pulse laser, 0.15 billion euros): Development of a high-peak power laser, aiming at an output of 100 petawatt, and research on application thereof
- XFEL (Hard X-ray free-electron laser, 1 billion euros): Development of an XFEL of the wavelength of 0.09nm using a superconducting linear accelerator, and research on application thereof

- FEL (Infrared to soft X-ray complementary free electron laser, 0.76 billion euros): Generation of FEL light from the infrared to ultra-violet/soft X-rays, and research on application thereof
- ESRF (Upgrade of the European synchrotron radiation facility, 0.23 billion euros): Upgrade to a next-generation synchrotron radiation facility

In addition, the following agenda were formulated at a forum consisting of a total of 350 related organizations (mainly those in the optoelectronics industry), including investors, named "Photonics 21" (formed in 2005), with the aim of creating new industries.

- Increasing investments in research and development in the European optoelectronics industry from the current 330 million euros per year by 10% annually
- Doubling cooperative research expenditure on photonics under the FP7 from those under the FP6
- Doubling each country's joint research expenditure on photonics over the next five years

② United Kingdom

Research on photon S&T in the United Kingdom is being energetically promoted at the initiative of the CCLRC (Council for the Central Laboratory of the Research Councils; established in 1995), mainly using high-power laser and synchrotron radiation facilities at the Rutherford Appleton Laboratory.

Also in a photon S&T-related project titled "EEMS: Exploiting the Electromagnetic Spectrum" (launched in 2004) under the UK Foresight Programme, research and development is ongoing, focusing on optical data/handling, photonics on the molecular level, noninvasive imaging, near-field optics and creation of metamaterials.

③ France

In France, the Laser Mega Joule (LMJ) was constructed in the Bordeaux (Aquitaine) region, and a high-tech industrial park was formed in the Ile-de-France region. Thereby, active research and development are being conducted in relation to advanced photon S&T. In particular, the EU recognizes optical communications technology as the "research infrastructure in Europe," and many projects have been implemented on collaboration between research institutes and the industry. In addition, research is also ongoing with regard to quantum cascade laser, attosecond pulses, X-ray laser, free electron laser, quantum optics, nonlinear optics, photorefractive effect, metamaterials and organic EL. A plan for the independent development of part of ELI (proposed to the ESFRI in the EU) in France was approved, and thus, various research institutes started development in an integrated manner.

④ Germany

In Germany, photon S&T are recognized strongly as important technology that forms the backbone of employment creation and economy. The stepwise promotion of measures relating to photonics by the Bundesministerium für Bildung und Forschung (BMBF) and efforts at network industrial clusters (organized through industry-academia-government collaboration and cooperation) mainly in eight regions are distinctive characteristics.

In a basic S&T policy titled "High-Tech Strategy for Germany" (launched in 2006), which was formulated by the current Merkel administration, photon S&T are clearly positioned as one of the pillars of 17 cutting-edge fields with high potential, in which investment should be made in a strategic manner. The 21st century is the "century of the photon." Therefore, Germany aims to achieve the following goals through creation of new industries by integrating photon tools and their various natures: by 2010, increasing the number of optoelectronics industry-related companies to 1,000, creating about 36,000 new employment opportunities, and achieving a growth rate exceeding 40%.

Present main research subjects relating to photon S&T consist of six pillars, specifically, terahertz science, femtosecond laser, high-efficiency diode laser, bio-optics (cancer treatment), organic EL and metamaterials.

(3) China

Laser development/production is concentrated in the periphery of six major cities (Beijing, Changchun, Shanghai, Shenzhen, Tianjin and Xian) and one special development zone (Wuhan East Lake Hi-Tech Development Zone). Development of a large high-energy laser is under construction as a national strategic technology at the Shanghai Institute of Optics and Fine Mechanics and the Chinese Academy of Engineering Physics in Mianyang, at the initiative of the National High Tech Committee. Thereby, China is following the United States and France in terms of the development of an ultra-high-intensity laser. In addition, China is actively working on research and development in photon S&T. For example, investments are focused on construction of a high-power extremely short-pulse laser and the Shanghai Synchrotron Radiation Facility. China is also expected to fully enter the optoelectronics industry on the basis of its technology for producing excellent photonic materials. Therefore, China may achieve an astounding rapid growth in the near future.

3. Current Situation and Problems in Japan

(1) Current situation of research at universities and public research institutes, etc.

Photon S&T constitute a fundamental field that cuts across eight fields which should be intensively promoted, including information and telecommunications, nanotechnology/materials, life science, the environment and energy, etc. Therefore, photon S&T-related research projects are ongoing at many universities and public research institutes, etc., though research courses and majors named "photon science" are rare. The current situation of major research and development projects relating to photon S&T and that of research institutes, etc. are as follows.

① Major research and development projects

A large synchrotron radiation facility (SPring-8), which generates the world's highest intensity synchrotron radiation, is shared by researchers in wide-ranging fields, including life science, substance/material, the environment and industrial application (fiscal 2007 budget: 9.3 billion yen). In addition, RIKEN, the Japan Atomic Energy Agency (JAEA) and other research institutes are carrying out research and development in photon S&T (fiscal 2007 budget: 2.4 billion yen).

Moreover, the world's highest performance X-ray free-electron laser (XFEL) with a high intensity exceeding a billion times that of SPring-8 is now under development. Its completion is expected in fiscal 2010 (fiscal 2007 budget: 7.5 billion yen).

Furthermore, other than SPring-8, which generates synchrotron radiation in the X-ray-to-hard-X-ray region, the Ultraviolet Synchrotron Orbital Radiation Facility (UVSOR) (at the Institute for Molecular Science in the National Institutes of Natural Sciences) focusing on the vacuum ultraviolet region and the Photon Factory (PF) (at the High Energy Accelerator Research Organization) focusing on the soft X-ray–to-X-ray region are continuously playing important roles. In addition, some large synchrotron radiation facilities, according to individual purposes and usages, have already been put into practice (running expenses for large synchrotron radiation facilities other than SPring-8: about 4.5 billion yen annually).

Other than these, under the Basic Research Programs, basic target-oriented research projects are being implemented based on the national S&T policy and social/economic needs, toward achieving strategic objectives set by the government. From the fiscal 2007 budget, about 2.8 billion yen was allocated to research relating to photon S&T. Also, in leading projects that are implemented for economic revitalization, research and development projects relating to photon S&T are in place (scheduled to end in fiscal 2007).

On the other hand, under Grant-in-Aid for Scientific Research, creative/pioneer academic research projects based on the freewheeling thinking of researchers are ongoing. Although the adopted individual research issues include those related to photon science, the details of research areas are set in research fields such as mathematical/physical science and engineering.

In addition, germinating and basic research is conducted at many universities of S&T, with the use of subsidies for operating expenses, etc. Also, public research institutes, such as the National Institute of Information and Communications Technology and the Advanced Industrial S&T, are carrying out research and development relating to optical information and communications and laser devices. It seems that about 40 to 50 billion yen are annually invested, at a moderate estimate, in Japan as a whole.

② Major research institutes in the field of photon science and technology (see Appendix 2)

Major universities and inter-university research institutes that conduct research on photon S&T include the University of Tokyo, the Institute for Laser Science at the University of Electro-Communications, the Institute of Laser Engineering at Osaka University, and the Institute for Molecular Science at the National Institutes of Natural Sciences. Regarding independent administrative agencies, etc., shared use of SPring-8 is carried out at the RIKEN Harima Institute, while extreme photonics research is conducted at the RIKEN Discovery Research Institute. The Kansai Photon Science Institute of JAEA is conducting research on photon quantum science and research on the application of synchrotron radiation. There are 25 research bases that are the same size as these research institutes. Also, activities in units of laboratories are conducted at many research institutes and universities of S&T.

The following table shows major large-synchrotron radiation facilities and laser facilities in Japan (Table 1).

Table 1. Major large-synchrotron radiation facilities and laser facilities

Major large-synchrotron radiation facilities	Research institutes
SPring-8	RIKEN Harima Institute Japan Synchrotron Radiation Research Institute
New SUBARU	University of Hyogo
Photon Factory: PF ring	High Energy Accelerator Research Organization
Photon Factory: PF-AR ring	High Energy Accelerator Research Organization
UVSOR	Institute for Molecular Science, National Institutes of Natural Sciences
SR Center	Ritsumeikan University
HiSOR	Hiroshima Synchrotron Radiation Center, Hiroshima University
SAGA LS	Saga Prefectural Regional Industry Support Center

Major laser facilities	Research institutes
Ultrashort-pulse high-power laser	Institute for Solid State Physics, University of Tokyo
Subfemtosecond laser	RIKEN Discovery Research Institute
High-power fiber laser/ceramic laser	Institute for Laser Science, University of Electro-Communications
Petawatt titanium-sapphire laser	Kansai Photon Science Institute, Japan Atomic Energy Agency
Multibeam laser for implosion of fusion/laser for high-speed ignition	Institute of Laser Engineering, Osaka University
Free electron laser	RIKEN Harima Institute Kansai Photon Science Institute, Japan Atomic Energy Agency Tokyo University of Science Graduate School of Engineering, Osaka University

On the other hand, it is difficult to statistically figure out the accurate number of researchers in the field of photon S&T as photon science has yet to be established as an educational field in Japan and there are almost no independent graduate courses in photon science. However, taking into account basic photon science, including photophysics, photochemistry and photobiology, and photon-based technologies, including electronic engineering, communication engineering, instrumentation engineering, chemical engineering, medical application and agricultural application, the number of researchers in relevant fields at major research institutes that are promoting photon S&T is estimated to be around tens of thousands.

(2) Past research results

Also in Japan, improvement and development of the world's highest-performance large research institutes, including SPring-8 and X-ray free-electron laser (XFEL), is being promoted in a concentrated manner, and diversified types of application research are implemented using light mainly in X-ray region.

① SPring-8

In terms of application research using SPring-8, outstanding results have been achieved in life science research relating to clarification of a three-dimensional structure of a protein that causes liver cancer, etc., or of a mechanism of carrying genetic information of DNA, and in wide-ranging material science research relating to clarification of a mechanism of superconductivity or ferromagnetism. In addition, industrial application is active, including contribution to practical application of an intelligent catalyst for automobile emissions as well as research and development for improving the performance of high-density semiconductors or fuel cells. Moreover, upgrading to a next-generation synchrotron radiation that enables measurement of transient phenomena and focusing light into a small spot is now under consideration.

② X-ray free-electron laser (XFEL)

With respect to XFEL toward completion by the end of fiscal 2010, actual equipment is in the production process on the basis of prototype equipment which succeeded in laser oscillation in June 2006. A high-intensity femtosecond pulse X-ray laser beam is expected to contribute to the development of new research areas in various fields of S&T, including the fields of life science and nanotechnology/materials. Examples are atomic-level ultramicrostructure, and instantaneous measurement and analysis of ultrafast dynamic and change of chemical reaction, as well as analysis of monomolecular structure without requiring crystallization of proteins.

③ Others

In addition to these large-scale projects, public research institutes and university-affiliated research centers are promoting advanced research that leads the world in terms of research and development as well as application of high-intensity lasers. They are also carrying out extensive development of various light sources, which are characterized by the nature of light emitted (wavelength, coherence, output, pulse width, number of cycles, etc.), and research on their application.

Out of research results developed independently in Japan, the particular ones that lead the world are listed below.

- Vertical-cavity surface-emitting laser (VCSEL) diode
- Photonics crystal
- Ceramic laser element
- Laser acceleration
- Photocatalyst
- Research on photochemical reaction
- Research on the optical property of nanostructures and supramolecules systems
- Optical lattice clocks
- Quantum teleportation technology
- X-ray nonlinear optics

Moreover, basic pioneer research projects are in progress, for example, control of chemical reaction using an extremely short-pulse laser and search for new functional materials. Some of the basic research projects in the field of photon S&T in Japan are highly praised in the international community.

(3) Future issues

As seen in the above, the world's most advanced research results have been achieved in Japan, using SPring-8. In addition, Japan tops the world in some of the elemental technologies for advanced photon tools, such as the VCSEL diode and the ceramic laser element. Thus, Japan has the potential to develop original epoch-making light sources using these technologies.

However, differently from the United States, Germany and other advanced countries in Europe, the field of photon S&T is not positioned as a policy pillar in Japan. There are no projects to strongly promote the said field, except for specific areas, such as improvement and development of SPring-8 and XFEL. In addition, although the field of photon science is a key field common to wide-ranging fields, it has hardly been established as an independent academic area in Japan. Also, educational research courses advocating photon science are hard to find.

Looking at the current situation, many researchers and research institutes relating to photon S&T are scattered throughout Japan, and it cannot be said that concentration of potentials through networking is sufficiently pursued. In addition, although many research projects are conducted using existing light sources, which were made in the United States and European countries, in all priority fields, not many researchers (strategic partners) sufficiently utilize cutting-edge photon tools with the full knowledge of their nature. Also, it cannot be said that cooperation between researchers in the field of photon S&T who create cutting-edge photon tools and strategic partners is frequent. Consequently, development of light sources and basic research on photon tools are conducted individually without sufficient reflection of needs in relevant fields.

For the future, researchers in the field of photon S&T as well as in relevant fields in Japan are required to aim for the world's best through concentration of excellent human resources. This is expected by creating a flexible organization to integrate the development of optical measurement, manufacturing, etc. with the development of light sources as an axis, while sufficiently reflecting needs in each priority S&T field.

(4) Current situation and problems in the industry

Looking at the global market scale of the optoelectronics industry, it was 29 trillion yen in 2002, and is expected to expand to 60 trillion yen in 2010 and 107 trillion yen in 2015. On the other hand, the scale of production in Japan was six trillion yen in 2002, and is expected to expand to 13 trillion yen in 2010 and 23 trillion yen in 2015. Japan is expected to get a global market share of more than 20% (from Optoelectronic Industry and Technology Development Association, "Future Vision of the Optoelectronics Industry (fiscal 2004)").

In addition, the scale of employment creation in the domestic optoelectronics industry as of fiscal 2006 is assumed to be about 140 thousand (estimated based on Optoelectronic Industry and Technology Development Association, "Trends of the Optoelectronics Industry (fiscal 2006).")

In this manner, optoelectronics industry-related fields have been promoted as an industrial strength, based on the recognition that the introduction of photon S&T will serve as a driving force for new industries. Actually, Japanese companies have high international competitiveness in the fields of optical information and communications and solar batteries. Moreover, looking at Japanese electric appliance and electronics manufacturers, they maintain a high production capacity for the carbon dioxide laser, excimer laser, light-emitting diode and semiconductor laser for communications.

However, looking at the trends of the global market, a high-efficiency/long-lived high-power semiconductor laser and fiber lasers using the said laser are expected to become mainstream in succession to the carbon dioxide laser in the near future. However, Japan is behind other countries for these lasers in the global market. A high-power semiconductor laser is essential not only for industrial use but also for the development of light sources in the entire field of photon S&T since it is the most suitable light source for solid-state laser excitation. Many Japanese companies are reluctant to develop advanced light sources that have high potential but currently low demand. Therefore, Japan's optoelectronics industry can lose competitiveness in the global market in the future.

If, in addition to conventional efforts, Japan promotes active research and development of advanced research equipment, which involves many development elements though its demand is low at present, before it loses the potential for elemental technologies for advanced photon tools, it will be able to improve international competitiveness in the development of high value-added advanced light sources and measuring equipment in the long term. Thereby, the possibility of Japan's creating innovation will dramatically increase.

(5) Current situation and problems in human resources development

Photon S&T is a complex and interdisciplinary academic area. It expands from classic photonics to spectroscopy, quantum mechanics, quantum chemistry, furthermore to quantum electronics and laser engineering, and develops while involving physics, chemistry, materials science, biology and medical science. Although rearrangement of knowledge and restructuring of an educational model based on the above fact are being requested, education on photon S&T is now provided discretely, at many universities, as part of the existing disciplines, such as physics, chemistry and electrical/electronic engineering.

To the contrary, for example, in the United States, research on cutting-edge photon S&T is being promoted at educational research centers such as the College of Optical Sciences at the University of Arizona. In addition, those educational research centers are focusing their efforts on the development of young researchers by enriching educational curriculum for learning photon S&T in an organized and systematic manner.

Also in Japan, the University of Tokyo, the University of Electro-Communications, and Keio University have recently formed the “Consortium for Education and Research on Advanced Lasers” in fiscal 2007, and hereby have been promoting establishment of an educational model for learning cutting-edge photon S&T in a systematic manner. However, such a model has yet to be generalized.

The Third S&T Basic Plan puts emphasis on “from hard to soft such as human resources” and human resources development. However, looking at the current situation of science and engineering departments at universities, it is very difficult to maintain the quality and quantity of young researchers. For example, the number of those who apply for engineering departments reduced by half in 10 years. Under such circumstances, photon S&T are among the attractive fields that may interest many young people, as the subject is “light” that is familiar in daily life. Therefore, active promotion of photon S&T is also requested from the viewpoint of fostering and securing S&T personnel for the future.

In Japan, there is a call for the development of young researchers through provision of organized and systematic education on photon S&T at universities and graduate schools as well as promotion of research in photon S&T.

4. Research in Advanced Photon Science and Technology

(1) Idea of priority-setting in future research and development

In promoting research in photon S&T, it is indispensable to establish a research and development system, and also to set priority on research and development issues from the perspective of effective and efficient utilization of limited financial sources. In priority-setting, the following points have to be taken into account.

- S&T fields, in which Japan is at the world's cutting-edge level in terms of academic activity or industrial technology and which Japan should further strengthen
- S&T fields that Japan should strengthen to ensure international competitiveness because the fields are considered to be particularly important, though Japan is not necessarily strong therein
- S&T fields that are expected to become important from the perspective of academic activity or industrial technology 10 to 20 years later

In addition, taking into account that photon S&T are among the few fields that may interest young researchers, it is important to prepare opportunities for challenge, which serve as a driving force for young researchers, in selecting and implementing these research and development issues.

It is necessary to select, based on this idea, issues to which priority should be given, and input research and development funds in an efficient manner.

(2) Exploitation of "new photon tools" and promotion of application research thereon

In order to further advance current photon S&T and lead to new innovation in each priority S&T field, it is necessary to develop advanced "new photon tools" in which the nature of photon tools has been upgraded more than ever before and to actively promote application research, etc. that becomes available through such development. In promoting these types of research, it is important to sufficiently utilize computer science and theoretical analysis to predict research direction. In particular, it is indispensable to support light source design and application research by actively promoting the establishment of a computation model that comprehensively imitates interactions between light and substance with the use of a supercomputer.

Examples of innovation expected to be realized by "new photon tools" are shown below.

① Clarification and control of chemical reaction processes

② Small/low-cost cancer treatment equipment, nondestructive imaging/nuclear waste management using high-intensity γ-ray, and fusion-based new energy source

③ Technology for detecting foreign substances (hazardous materials/tumors) by living cellular diagnosis or by clear transparent images without exposure

④ Processing technology using clean and energy-saving photon tools, which is applicable in various industrial fields

⑤ Undecipherable optical cryptography and ultrahigh-capacity/ultrahigh-speed optical information and communications technology

⑥ Cutting-edge nanomedicine and optoelectronics industry using new processes of crystal growth/nanoparticulation by means of laser beam

Research and development issues for achievement of these innovations are shown below.

① Research for "clarification and control of chemical reaction processes"

If extremely short-pulsed light, of which the laser amplitude or wave form is adjusted, is irradiated to a substance, the quantum state (information) of light is transferred to electrons. It is possible to dissociate a specific atom (molecule) or bring a new combined state with substituting the chemically bonded atoms by controlling the electronic state. Hereby, it is expected to be possible to realize specific chemical reactions or new chemical reactions, which do not occur in conventional thermal chemical reactions, by means of light. If such a method becomes possible, an expansive new field will arise, that is, the creation of new substances by means of light.

[Current condition of research]

- Basic research is being conducted in relation to the control of the dissociation/combination process of ethanol and other low-molecular substances and the selection of a specific electronic state.

[Challenges in research and development]

- Clarification of a molecular energy relaxation phenomena in various conditions (in a gas, in a liquid, in a solid matter, at the surface, at the interface, etc.), and control of chemical reactions

[New technologies, etc. expected to be realized]

- Control of complex reactions in a supramolecular system or a biological system
- Clarification/control of the process of producing harmful byproducts
- Establishment of the concept of new chemical reactions by means of light and new isotope-separation method based thereon

[Development of "new photon tools" that are needed]　(see Figure 2)

To study time change of electrons that govern chemical reactions, light with an extremely short-pulse width (in the attosecond domain (10^{-18})) is necessary. It is possible to control a chemical reaction by using only light, of which frequency, phase, amplitude and polarization are completely controlled. At present, sub-femtosecond (10^{-16}) pulse laser beam is available. A promising method is conversion into an attosecond coherent light pulse by nonlinear effect using noble gas or by a flying mirror of light velocity (reflection by high-density plasma). The wavelength of such light corresponds to the X-ray region (0.3 to 30nm). Therefore, it is important to also carry out development of optical devices for particular X-rays, such as high-performance X-ray mirrors, X-ray diffraction gratings and X-ray polarizers.

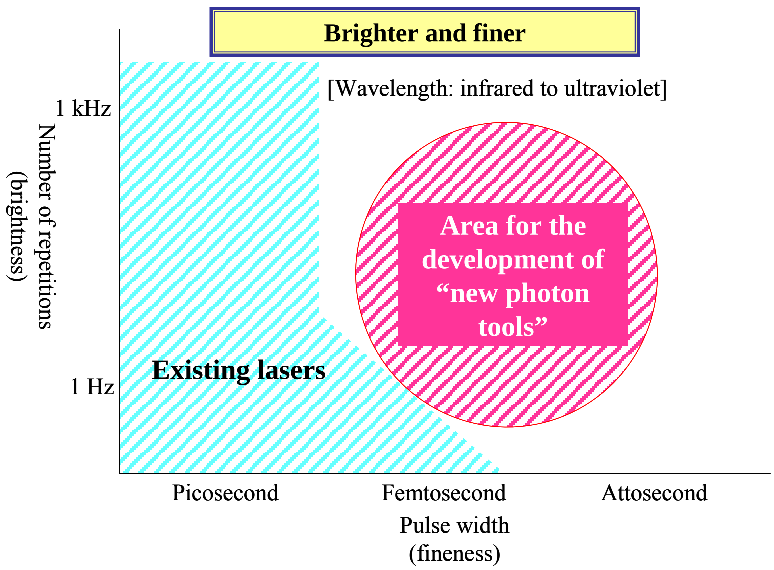


Figure 2. Area for the development of "new photon tools" (1)

② Research for "small/low-cost cancer treatment equipment, nondestructive imaging/nuclear waste management using high-intensity γ-ray, and fusion-based new energy source"

By focusing a high-intensity/short-pulse laser beam on low-density gas, it is possible to generate an extremely strong accelerated electric field, which exceeds the thousand to ten thousand times of the acceleration limit (10MeV/m) of an ordinary accelerator. Therefore, it is possible to significantly downsize accelerators, which enables accelerating electrons and ions and generating X-rays and γ-rays with the use of small equipment without requiring the conventional large facilities. Such quantum beam has characteristics that conventional radiation rays do not have, such as high-intensity, extremely short-pulse and low emittance. Therefore, it is expected to be used in new ways in various fields. In addition, the ultrahigh pressure/temperature extreme state, created by focusing high-intensity laser beams of which energy are identical, is important in developing nuclear fusion that will be a future energy source.

[Current condition of research]

Acceleration of electrons

- 1GeV electrons are generated by three-cm laser acceleration.

Generation of quantum beam

- High-quality coherent X-rays (in the 0.1keV region) and short-pulse X-rays in the wide range (several tens eV to MeV) are generated.
- Proton beam of several tens MeV is generated.

Creation of the extreme state

- The high-pressure/high-temperature state (a thousand times of the pressure within the earth and 100 million ºC) is generated by laser fusion.

[Challenges in research and development]

Acceleration of electrons

- Realization of 10GeV-class high-energy electron acceleration by a dozens-of-centimeters-long accelerated electric field, etc.

Generation of quantum beam

- Research on high-definition imaging using a coherent X-ray for high-sensitivity light measurement to discriminate those that are usually invisible or those that are indistinguishable by appearance, research on a high-sensitivity analysis method for EXAFS (Extended X-ray Absorption Fine Structure) with time resolution that is orders of magnitude higher than in the past, and research on PIXE (Particle Induced X-ray Emission) analysis method using protons in the micro space in the nanometer range
- Research on technology for generating inverse Compton γ-ray for nondestructive inspection, which does not require a nuclear reactor, etc.

Creation of the extreme state

- Creation of the extreme state, such as the state under the pressure of petapascal (10 thousand times of the pressure within the earth) and the state at the temperature exceeding billion ºC, and research on the reforming of a substance and expression of a new state as well as research on creation of a new substance
- Clarification of space phenomena through laboratory simulations relating to generation and extinction of planets and stars, etc.

[New technologies, etc. expected to be realized]

Acceleration of electrons/ions

- Realization of TeV-class high-energy electron acceleration by a few-meter accelerated electric field, and realization of GeV-class ion acceleration

Generation of quantum beam

- Realization of heavy particle radiation for cancer treatment
- Application of high-intensity X-ray for cancer treatment, etc., and utilization of high-intensity γ-ray for nuclear waste management
- Creation of new materials and upgrading of fine processing technology, by means of quantum beam

Creation of the extreme state

- Clarification and control of new phenomena accompanying the generation of a strong photon field by focusing light
- Upgrading of the high-speed ignition mechanism in the development of nuclear fusion energy

[Development of "new photon tools" that are needed] (see Figure 3)

For this research, an ultra-high-intensity laser beam with an extremely high-peak output and increased frequency (high-repetition) is necessary. At present, a petawatt (10^{15}: a few hundred times of average power consumption in the world) laser beam is available using a titanium doped sapphire laser. In this case, pulsed light is repeatedly output once about every ten seconds. In addition, conversion efficiency from electricity to laser beam is low at below 0.1%. For the progress of application research, petawatt-over light source, which can generate pulsed light with a high repetition rate exceeding10Hz (10 times per second) and with a high efficiency of about 10%, is indispensable. A promising light source is a system in which ytterbium (Yb^{3+}) ceramics is directly excited by a high-efficiency, high-power semiconductor laser. The efficiency of laser can be improved by a high excitation efficiency obtained by using a high-power semiconductor laser. Also, laser ceramics developed in Japan are expected to achieve high repetition as it has excellent cooling characteristics as with laser crystal.

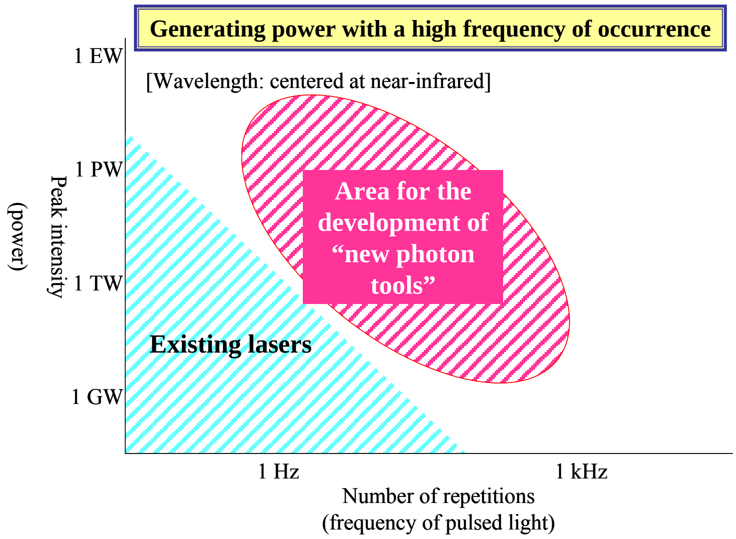


Figure 3. Area for the development of "new photon tools" (2)

③ Research for "technology for detecting foreign substances by living cellular diagnosis or by clear transparent images without exposure"

Soft X-ray light and terahertz far-infrared light are in a region that has yet to be exploited up to now. Soft X-ray with a wavelength of 2 to 4nm is called a "water-window," and it is in the wavelength region that is suitable for direct observation of living microscopic cells. If a user-friendly light source is achieved, it is expected to bring innovation to life science. For example, it will become possible to directly observe the process of protein synthesis. On the other hand, terahertz light has already started to be used for analysis of biopolymer structures and safe nondestructive inspection without exposure. Terahertz light is expected to be widely applied in the future as it can be easily generated using small equipment.

[Current condition of research]

- Structural change of crystal is observed by means of an X-ray laser, but application of coherent soft X-ray is still limited.
- 0.5 to 3 THz light is already in use as a light source for analytical equipment relating to safety and security, such as equipment for nondestructive inspection of mail matters.

[Challenges in research and development]

- Generation of coherent soft X-ray in the "water-window" region, and dynamic observation of living cells using it
- Generation of high-intensity coherent terahertz light
- Development of a sensor for rescue that enables prompt finding of people in the case of a fire/driftage/distress in a snow-capped mountain, etc.

[New technology, etc. expected to be realized]

- Analysis of protein structure and analysis of industrial materials/medical products, based on the measurement of vibrational/rotational state of molecules
- Environmental measurement technology that enables high-sensitivity measurement of pollutants as well as endocrine disruptors
- High-sensitivity imaging of the seat of disease by cellular diagnosis or by optical CT measurement

[Development of "new photon tools" that are needed] (see Figure 4)

At present, a coherent X-ray laser in the soft X-ray region of about 10nm and far-infrared light in the terahertz range (0.1 to 40THz) are available.

For soft X-ray, it is necessary to shorten the wavelength of a plasma X-ray laser and increase the repetition thereof as well as to shorten the wavelength of higher harmonic light and increase the power output thereof. For terahertz light, various types of research on generation are expected to be conducted, such as generation of coherent terahertz light by means of a small light source suited for practical use, quantum cascade laser, or accelerator, etc.

In addition, the development of the following is important: selective fluorescent labeling that distinctively indicates the seat of cancer, high-sensitivity sensor, compensation optical system that is necessary to obtain high-definition images, image processing method, etc.

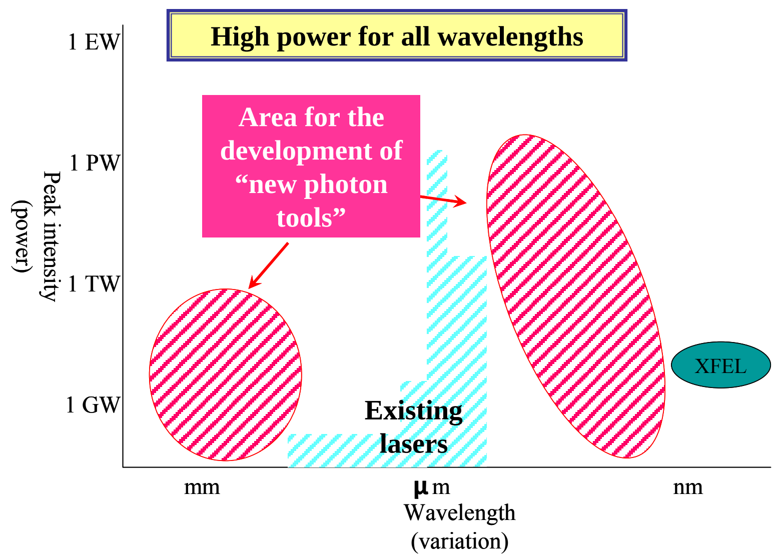


Figure 4. Area for the development of "new photon tools" (3)

④ Research for “processing technology using clean and energy-saving photon tools, which is applicable in various industrial fields”

In addition to the upgrading of thermal processing technology by which the subject to be processed is given high temperature by a focused laser beam and is thereby melted and processed, it is important to use a short-pulse laser beam to establish nonthermal processing that does not involve heat. These laser-processing technologies adopt the contactless approach, which is different from conventional contact-type croppers and welders. Therefore, there is no expendable part, and thus, dust can be kept to the minimum. In addition, these later technologies can be widely used for processing complex shapes and different materials. Moreover, high-speed processing is possible, and energy consumption at the time of processing can be kept low. Consequently, these laser-processing technologies are becoming indispensable means for innovation of production technology.

[Current condition of research]

- Welding, cutting and surface modification of metals as well as forming of new materials are being conducted using thermal processing technology.
- Nonthermal fine processing of metals and semiconductors and elimination of stress strained layers are being conducted using an extremely short-pulse laser beam.
- Basic research is being conducted in relation to nonthermal fine processing in transparent materials using an extremely short-pulse laser beam as well as in relation to the manufacturing of metamaterials that are new optical materials.

[Challenges in research and development]

- Development of high-efficiency/high-directivity/high-power semiconductor lasers
- Development of new small/high-efficiency/high-power lasers, including high-power semiconductor laser-pumped fiber lasers and solid-state lasers
- Basic research for new application fields, such as research on interaction between an extremely short-pulse laser beam and biological materials, etc.

[New technologies, etc. expected to be realized]

- Realization of innovation of production technology
- Dissemination of extensive application technology using extremely short-pulse laser

[Development of “new photon tools” that are needed]

At present, the carbon dioxide laser (laser efficiency: up to 2%; oscillation wavelength: 10.6μm) is mainly used for thermal processing. The high-output semiconductor laser of which electricity-light conversion efficiency is 70% or higher, Yb^{3+} fiber laser pumped thereby, and solid-state laser can keep energy consumption necessary for processing at a lower level, as they can achieve a high laser efficiency, longer operating time, and narrow processing width. New technology through a combination of VCSEL and photonic crystal is promising as a method of improving the light-focusing ability of an existing semiconductor laser and upgrading it to an increasingly high-efficiency/high-power laser light source. Such high-power semiconductor laser-pumped fiber laser and solid-state laser can be utilized for generating an extremely short-pulse laser beam for nonthermal processing.

⑤ Research for "undecipherable optical cryptography and ultrahigh-capacity/ultrahigh-speed optical information and communications technology"

If atoms are cooled to extremely low temperatures with the use of a laser beam, Bose-Einstein condensation is formed in which the entire group of the atoms behaves as a matter wave. Evolving the research subject to molecules or solid matters is expected to bring about revolutionary progress to solid-state physics and chemistry, including clarification of superconductivity and superfluid phenomena based on the similar BEC state and expression of a new matter state that does not exist in the natural world. Moreover, technology for freely operating phenomena of simultaneous occurrence of two or more states, which are particular to quantum mechanics, serves as epoch-making technology that brings out the potential of light. Examples of such technology are quantum cryptography and quantum information-processing that enables communication of a large quantity of information.

[Current condition of research]

- BEC using lean gas atoms and one-dimensional optical lattice clocks with 15-digit frequency accuracy, and control of tripartite quantum entanglement have been realized.
- Research is being conducted in relation to the cooling of molecular gas of which temperature is at the millikelvin level, realization of BEC of metastable molecules using cooled atoms, and the orderly state generated by interaction between coherent light and electron.

[Challenges in research and development]

- Achievement of an optical lattice clock with a 17-digit high frequency accuracy (absolute frequency) and realization thereof as a frequency standard, as well as precision measurement using it
- Realization of the extremely low-temperature/high-density BEC state, etc.

[New technologies, etc. expected to be realized]

- Panoramic understanding of physical phenomena in a strongly correlated system (system in which electrons act while strongly correlating with each other), as well as clarification of a mechanism of high-temperature superconductivity based thereon and creation of new physical phenomena in a strongly correlated electron system
- Exploitation of science using the characteristics of extremely low-temperature molecules
- Establishment of high-density information-storage/processing technology and high-speed optical information-processing technology (quantum computer), by means of photon tools

[Development of "new photon tools" that are needed]

For this research, not only a light source with a high frequency stability and extremely small power fluctuation for each pulse but also a light source of which phase, output power, pulse width, etc. in various wavelengths are completely controlled are necessary. Such light source is becoming possible owing to an optical frequency comb technique using an extremely short-pulse laser. However, further upgrading is necessary. In addition, by expanding this technique to the longer wavelength region, it is expected to be used as a frequency standard for infinitesimal analysis of various substances and for multiple optical communications in different communication bands in the future. A light source in which an optical frequency comb technique is combined with a mode-locked fiber laser is promising as a light source suited for application research.

⑥ Research for "Cutting-edge nanomedicine and optoelectronics industry using new processes of crystal growth/nanoparticulation by means of laser beam"

If an extremely short-pulse laser is irradiated to the high concentration solution of molecules or ions, a supersaturated state is created locally/transiently, and minute crystals are generated. Crystals grow larger with these minute crystals as the core. This epoch-making crystal growth method unique to Japan is expected to pave the way to crystallization of dendrimers, polymers and membrane proteins, which has been extremely difficult in the past, and thereby to give a significant impact on wide-ranging fields, including the fields of life science and material chemistry.

In addition, irradiation of a high-intensity pulse laser beam causes property modification from insoluble materials to soluble materials. If a solution in which insoluble solid matters are dispersed is irradiated with the laser beam, ablation of the solid matters will occur and nanoparticles will be generated. Scattered nanoparticles will be solubilized as stable colloids. These colloids are smaller in size compared to those obtained by other methods and can be equalized. They are also characterized by not including any additives for solubilization. Therefore, they are expected to make wide-ranging contributions to S&T relating to colloids and colloid-based industries, etc.

[Current condition of research]

- Regarding crystallization, a few groups are conducting research on the production of high-quality protein crystals and the mechanism of crystallization.
- Regarding nanoparticulation, research has been started in relation to various dyes, aromatic hydrocarbons and nanocarbons. Particularly, in terms of dyes, the world's smallest sized dye (13nm) has been obtained, and its application to color filters, inks, etc. is now under consideration.

[Challenges in research and development]

- Consideration of new methods of crystallization/nanoparticulation using newly developed light sources that bring about ionization, strong electric field, large amplitude motion, etc.
- Optimization for such conditions as the purity of the sample, solvent and temperature in the crystallization/nanoparticulation
- Implementation of systematic experiment (combinatorial chemistry) in relation to various laser parameters
- Consideration toward realization of downsizing of chemical plants, etc.

[New technologies, etc. expected to be realized]

- Achievement of crystallized dendrimers, polymers and proteins, and their application to electronic engineering, material engineering and optical engineering
- Contribution to the drug development industry through provision of advanced analytical information obtained with the use of high-quality protein crystals
- Application to sensors, solar batteries, devices, filters, displays, etc. by low-cost nanoparticulation technology
- Realization of anticancer agents and therapeutic agents for immunologic diseases, osteoporosis or other diseases by means of nanoparticulation technology

[Development of "new photon tools" that are needed]

At present, research is conducted using an excimer laser, solid-state ultraviolet laser and femtosecond titanium doped sapphire laser. The quality of crystals and the size of nanoparticles strongly depend on the parameters (wavelength, optical output, the number of repetitions, pulse width, etc.) of the laser beam irradiated. This research has just been started, and sufficient research has yet to be conducted regarding dependence on these parameters. For material development including crystal growth and nanoparticulation, a robust light source with a stable laser performance, of which parameters can be easily changed, is strongly required. Moreover, it is also indispensable to develop laser light sources with a new function, which will lead to production of new types of crystals and nanoparticles. It is also important, from the viewpoint of extensive use and practical application, to produce compact light sources of which performance is maintainable for a long time and to provide them at a low price.

The following tables summarize characteristics of "new photon tools" and examples of application research expected to be conducted in each field.

Table 2. Classifications of "new photon tools" that are necessary for application research

● Laser beam with an extremely short-pulse width Laser beam with a pulse-time width from picosecond to femtosecond and attosecond
Light source that is necessary for high-speed, large capacity optical communications, control of chemical reactions, material manufacturing, optical processing, quantitative analysis, environmental measurement and nanomedicine
● High-intensity laser beam Laser beam with a very high intensity of petawatt class, though its pulse-time width is short between picosecond and femtosecond
Light source that is necessary for material manufacturing, noninvasive diagnosis and cancer treatment, as well as nondestructive inspection and nuclear fusion energy
● Coherent soft X-ray laser beam and far-infrared light in the unexplored wavelength region Soft X-ray light and terahertz far-infrared light in the "water-window" region of the wavelength of 2 to 4nm
Light source that is necessary for cellular diagnosis and fluoroscopic examination without exposure
● High-precision laser beam Pulsed laser beam with a high frequency stability and little power fluctuation, and laser beam of which the phase is controlled with a high degree of precision
Light source that is necessary for quantum cryptography, large-capacity optical communications, high-speed optical information-processing technology (quantum computer), control of chemical reactions, quantitative analysis, pollution measurement and nanomedicine

Table 3. Examples of application research for "new photon tools" expected in each field

Field	Application research using "new photon tools"
IT (Information & telecommunications)	Quantum cryptography, large-capacity optical communications, high-speed information-processing (quantum computer), optical lattice clocks, etc.
Nanotechnology/materials	Control of chemical reactions, material manufacturing, optical processing, quantitative analysis, nondestructive inspection, etc.
Life science/safety and security	Cellular diagnosis, noninvasive diagnosis, cancer treatment, fluoroscopic examination without exposure, nanomedicine, etc.
Environment/energy	Environmental measurement (in water, air, and space), nuclear fusion energy, etc.

5. New Efforts to Promote Research in Photon Science and Technology

As mentioned above, photon S&T open up new areas through fusion with other fields, and induce epoch-making innovation. Therefore, countries other than Japan are also strategically developing photon S&T policies, and are promoting organic collaboration between researchers and engineers in various fields in the industry, academia and government sectors beyond the framework of organizations.

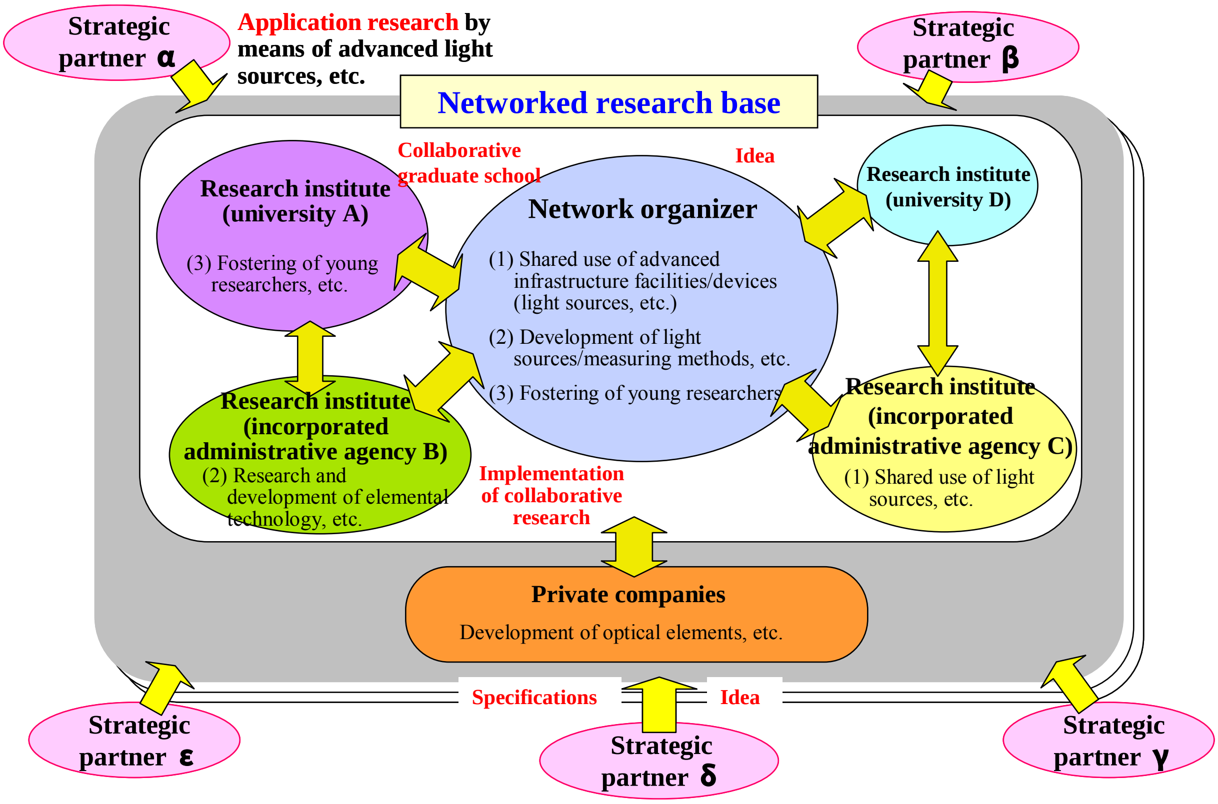
In order for Japan to gain a lead in the photon field without falling behind the United States and European countries in the future, it is necessary to further promote development and shared use of SPring-8, X-ray free-electron laser (XFEL) and other facilities. In addition, it is also necessary to establish a mechanism that enables various researchers in the industry, academia and government sectors to collaborate and fuse with each other by combining seeds in the field of photon S&T and the needs in other fields. Specifically, the following efforts are necessary.

(1) Developing "new photon tools" by concentrating the potentials of researchers, research institutes, industry, etc., and expanding application research
(2) Implementing strong programs to promote research in photon S&T

In addition, looking at the budget relating to photon S&T at MEXT, annual expenses necessary for shared use of SPring-8 (a large research facility) and development and shared use of XFEL exceed 20 billion yen. Adding various competitive research funds and subsidies for research institutes' operating expenses to the said expenses, about 50 billion yen is spent annually for photon S&T in all of Japan. It is necessary to continue to make investments of at least the same scale as now (about 50 billion yen annually) for the meantime, even after the completion of XFEL, due to the need to establish the above-mentioned new mechanism in addition to progress in the manufacturing of actual equipment of XFEL by the end of fiscal 2010 and shared use thereof, as well as the need to upgrade SPring-8. Hereby, it will be possible to promote active and consistent research and development in photon S&T, covering everything from basics to applications. In addition, the government as a whole can lead the industry's efforts for new research and development toward achieving innovation by conducting multifaceted activities.

(1) Concentration of potentials of researchers, research institutes, industry, etc. (see Figure 5)

In order to concentrate potentials in the field of photon S&T and other fields, it is important to establish networked research bases, in which research institutes, which are working on application research using photon tools, and researchers, industry, etc. participate, centering on several research institutes that are strongly promoting photon S&T. Particularly, in terms of collaboration with universities, the development of human resources who will lead the next generation is to be effectively promoted through vitalization of mutual exchange in research and education.



Strategic partners (SP) : Researchers & engineers driving application studies by means of new photon tools (lasers, equipments, etc) . SP in disparate fields are also prospective to expand research area.

Figure 5. Model of a networked research base (draft)

① Purposes of networked research bases

At networked research bases, researchers and engineers in various fields at optical manufactures and measuring equipment developers and manufacturers, which support research, collaborate and fuse with researchers and engineers in the field of photon S&T at universities and public research institutes, in an organic manner. This is to develop advanced control/measuring equipment using original light sources for realizing tools useful for application research.

Specifically, the following are promoted centering on several research institutes that are strongly promoting photon S&T.

- Developing and training strategic partners who can sufficiently utilize cutting-edge photon tools
- Conducting next-generation research in photon S&T focusing on research and development of new, unprecedented light sources and measuring methods

② Research and development system at networked research bases

It is important to develop and train strategic partners who can sufficiently utilize cutting-edge photon tools at networked research bases. Therefore, infrastructure equipment and devices, such as cutting-edge light sources, are developed, maintained and provided to be used for application research there.

By establishing a fluid research system that allows changing participating research institutes and researchers in a flexible manner, depending on the phase of research and development of light sources/measuring methods that is conducted to develop “new photon tools,” efficient research and development will be possible. This will also contribute to increasing the mobility and expertise of researchers.

③ Human resources development and establishment of photon science as a new science/academic area

Since networked research bases work on cutting-edge research and development through concentration of potentials in the field of photon S&T and in other fields based on photon tools, they may provide researchers participating therein with a rare opportunity to review their own research abilities. Therefore, it is desired that networked research bases actively develop, particularly, young researchers (postdoctorals, doctoral students, etc.) who will lead the next generation in photon S&T.

In addition, it is the engineers and technicians who play an active role in the industry that serve as the backbone of technology for manufacturing optical devices, which are indispensable for the development of light sources/measuring methods, etc. Consequently, networked research bases aim to maintain and upgrade the skills of these engineers and technicians.

Moreover, regarding photon science, which has not been prioritized in the past, the edifice of knowledge will be systematically organized as a new academic area covering the fields of science and engineering, including photonics, spectroscopy, electromagnetics, quantum mechanics, quantum chemistry, and laser engineering. Based on this, efforts will be made to develop higher education according to standard curriculums and models. On this basis, efforts will also be made to establish new areas of photon science/engineering, including applied mathematics, computer science, photochemistry, optical materials science, optical solid-state science, photobiology, photomedicine, precision engineering and control engineering, which are necessary for application in more wide-ranging fields, with the use of Grant-in-Aid for Scientific Research.

(2) Strong program for promoting research in photon science and technology

It is important that the establishment of the above-mentioned networked research bases makes progress through the self-help efforts of research institutes and researchers. However, measures based on the following two programs are proposed as schemes to further promote such networking by self-help efforts and to strongly promote collaboration and fusion with other fields: "program for new photon tools in public offering" (long-term program necessary for forming research bases) and "program for application studies in public offering" (exhaustive program in which photon tools available at present).

① "Program for new photon tools in public offering"

The purpose of this program is to establish networked research bases, in which the industry and researchers/research institutes, etc. some of which are conducting application research for photon tools participate, centering on several research institutes that are promoting research in the field of photon S&T, and thereby to promote human resources development and research and development of new light sources/measuring methods in an effective and efficient manner.

Under this program, research bases that have promoted networking through self-help efforts are requested to make proposals containing the following matters.

a. Developing and operating cutting-edge facilities relating to the existing light sources, etc. to provide them for use by strategic partners
b. Conducting research and development of new light sources/measuring methods, etc. by innovative methods that do not follow equipment/methods of the United States and European countries
c. Fostering young researchers who will lead the next-generation photon S&T

In particular, in promoting research and development of new light sources/measuring methods, etc. mentioned in b., it is necessary to involve a group of strategic partners from the design phase, in order to ensure that application research for cutting-edge photon tools can be immediately conducted with the effective use of facilities at the time of their completion in the future. Hereby, it is possible to work on the research and development of new light sources, etc. with the sufficient understanding of the needs of strategic partners. Specifically, research bases will work on the following research and development.

- Research that enables establishing "new photon tools" that will lead cutting-edge photon S&T from the ground up
- Consistent project research covering everything from manufacturing of a prototype to development of full-fledged equipment
- Research for the development of measuring methods/devices for the properties of "new photon tools" and new phenomena that are expressed due to the said properties

In developing new light sources/measuring methods, etc., it is necessary to develop optical elements, etc. with the performance that ready-made products do not have, and to evolve light sources and measuring equipment in the research phase into practical use. Therefore, the participation of private companies is indispensable for this program. Collaborative development with private companies is expected to lead to innovation, such as the creation of a new industry.

Also, in this program, a long research and development period over five years is required since networked research bases work on research and development for new light sources/measuring methods, etc., in which innovative methods and technology are introduced, from scratch. In order to promote a long-term project in a progressive, effective manner, the research and development period is divided into three phases, and verification of project effectiveness and review of research will be conducted as needed even at the midterm stage of the project.

② "Program for application studies in public offering"

The purpose of this program exists in that researchers who use photon tools in each priority S&T field try to develop totally new research directions and areas by utilizing cutting-edge light sources, etc. in unprecedented ways. For this purpose, strategic partners who promote research will work on active research and development in consideration of the following viewpoints, with strong support from light source developers who are versed in the principle of generating cutting-edge light and the performance and measuring methods thereof.

- Unique exhaustive research through existing cutting-edge light sources, etc., for example, by independently improving the existing light sources, etc. or by devising new applications
- Specific research for knowing, creating and communicating new matters by using elemental technology, beyond mere development of elemental technology such as development of optical devices

In the conventional ways of promoting programs, there have been quite a few cases where a research and development program for light sources/measuring methods, etc. implemented by researchers and developers in the field of photon S&T (on the seeds side) and a research program implemented by strategic partners (on the needs side) are implemented independently from each other. However, if these programs are implemented through collaboration and fusion with each other, they will not only bring about innovative research results unique to Japan to both the seeds and needs sides, but will also lead to the creation of further innovation in terms of industrial technologies, owing to synergy effect.

Therefore, it is also necessary to promote two different programs proposed above in a mutually complementary manner. In addition, efforts will be made to add fund conditions on the premise of "fused research" and to realize a research system that allows researchers to actively challenge high-risk, original research with patience. It is also important to think about a system that enables flexible research development in which trial-oriented (budding and fostering) research and target-oriented research are included, in order to achieve continuous creation of research results.

From these viewpoints, a program promotion and operation system that is different from the conventional one is to be proposed.

(3) Program promotion and operation system (see Figure 6)

A few Program Officers (POs) are placed for coherent management of research and development of light sources/measuring methods, etc. under the "program for new photon tools in public offering" and application research under the "program for application studies in public offering." POs are granted the great authority that is necessary for managing both programs. POs (up to three) select networked research bases and themes for application research by strategic partners, and patiently give guidance for the overall operation of projects, as well as conduct intermediate evaluation of projects in each period. Selection of POs and ex post evaluation at the end of projects are conducted by the Project Evaluation Committee (tentative name) that is composed of outside experts in the industry, academia and government sectors.

In addition, an evaluation of programs has to be conducted with emphasis on the spreading of results across the fields and impact on society and economy, which have been brought about through collaboration and fusion between research institutes and researchers/developers in the field of photon S&T and strategic partners in other fields. For this reason, it is necessary to consider new evaluation items in consideration of spillover effects on other fields and the impact on society and the economy, in addition to existing quantitative evaluation items, such as the number of papers and the number of patent applications.

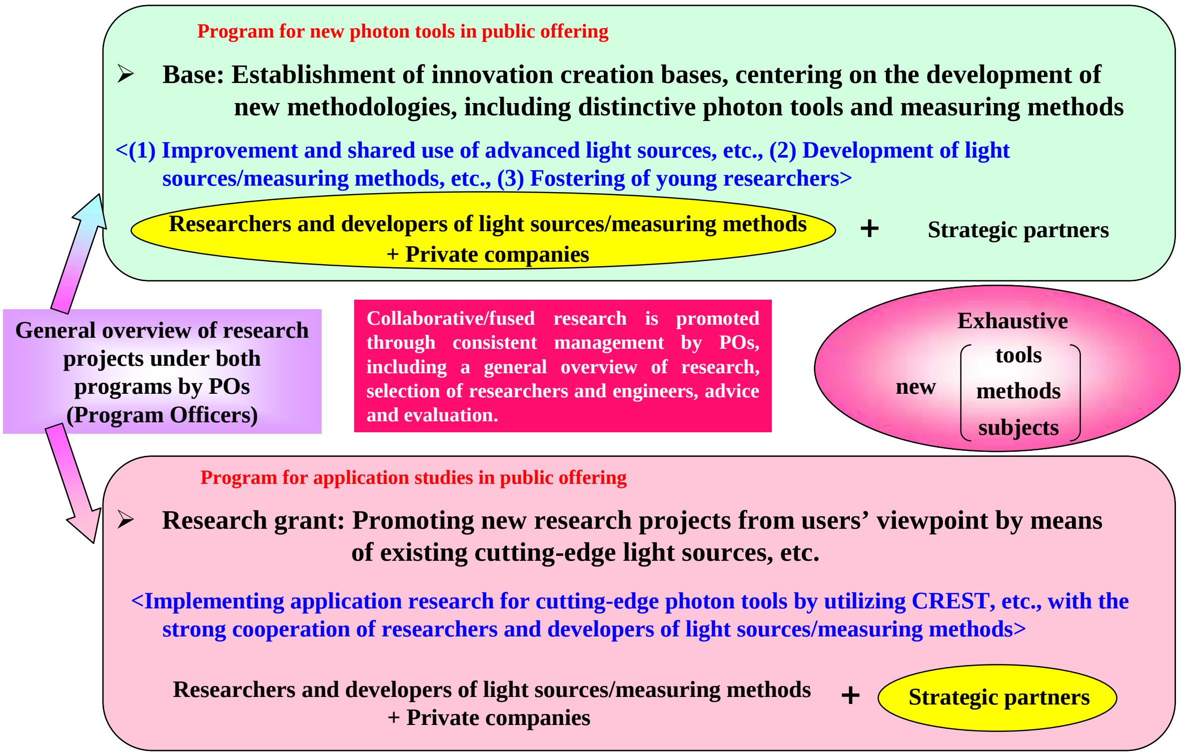


Figure 6. Scheme to promote research (draft)

List of Members of Special Task Force on Promotion of Photon Science and Technology

Chairperson

Yoshiaki KATO	(Director, Quantum Beam Science Directorate, Japan Atomic Energy Agency)

Members

Hiromasa ITO	(Visiting professor, Graduate School of Engineering, Tohoku University)
Ken-ichi UEDA	(Director, Institute for Laser Science, University of Electro-Communications)
Nobuyuki OSAKABE	(General Manager, Advanced Research Laboratory, Hitachi, Ltd.)
Hirofumi KAN	(Director, Central Research Laboratory, Hamamatsu Photonics K.K.)
Makoto GONOKAMI	(Professor, Graduate School of Engineering, University of Tokyo)
Kazunobu TANAKA	(Principal Fellow, Center for Research and Development Strategy, Japan Science and Technology Agency)
Hiroshi MASUHARA	(Chief Researcher, 21 Life Science Laboratory, Hamano Life Science Research Foundation)
Katsumi MIDORIKAWA	(Chief Scientist, RIKEN)
Kunioki MIMA	(Director, Institute of Laser Engineering, Osaka University)
Yoshiharu YONEKURA	(President, National Institute of Radiological Sciences)

(In the order of the Japanese)

Process of Deliberations

First meeting: Tuesday, February 27, 2007 18:00-20:00

- ○ Concerning the current condition and future of photon S&T
- ○ Others

Material 1: Concerning promotion of photon science (draft)

Second meeting: Wednesday, March 14, 2007 18:00-20:00

- ○ Concerning the way to promote measures for photon S&T in the future
- ○ Others

Material 1: Opinions on the promotion of photon S&T (draft)

Material 2: Way to promote measures for photon S&T in the future (draft)

Material 3: Schedule for the near term (draft)

Material 4: Overseas research schedule

Material 5: Information on the next and subsequent meetings

Third meeting: Monday, April 9, 2007 16:00-18:00

- ○ Concerning the way to promote measures for photon S&T in the future
- ○ Others

Material 1: Concerning the way to promote measures for photon S&T in the future (draft)

Material 2: Trends of research in photon S&T in other countries

Fourth meeting: Thursday, April 26, 2007 16:00-18:00

- ○ Concerning the way to promote measures for photon S&T in the future
- ○ Others

Appendix 1: Examples of Innovative Research, Including Nobel Prize-Winning Research

Nobel Prize in Physics

2001
Winners: C. Wieman (U.S), W. Ketterle (Germany), and E. Cornell (U.S.)
Reason: For the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates

2002
Winners: Masatoshi Koshiba (Japan) and Raymond Davis (U.S.)
Reason: For pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos
Relevant technology: Photomultiplier tubes

2005
Winner: Roy Glauber (U.S.)
Reason: For his contribution to the quantum theory of optical coherence

Winners: John Hall (U.S.) and Theodor W. Hänsch (Germany)
Reason: For their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique

2006
○ Winners: John Mather (U.S.) and George Smoot (U.S.)
Reason: For their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation

Nobel Prize in Chemistry

1995
Winners: Paul J. Crutzen (Netherlands), M. Molina (U.S.), and S. Rowland (U.S.)
Reason: For discovery of destruction of ozone lasers by nitrogen oxide and chlorofluorocarbon
Relevant technology: Laser spectroscopy method for measuring minor components in the air

1996
Winners: R. Curl (U.S.), R. Smalley (U.S.), and H. Kroto (U.K.)
Reason: For their achievement of discovering football-shaped C60 fullerene and thereby opening possibilities of electronic materials
Relevant technology: Laser evaporation cluster molecular beam

1999
Winner: A.H. Zewail (U.S.)
Reason: For his development of ultrashort analysis time for chemical reactions (femtosecond laser chemistry)

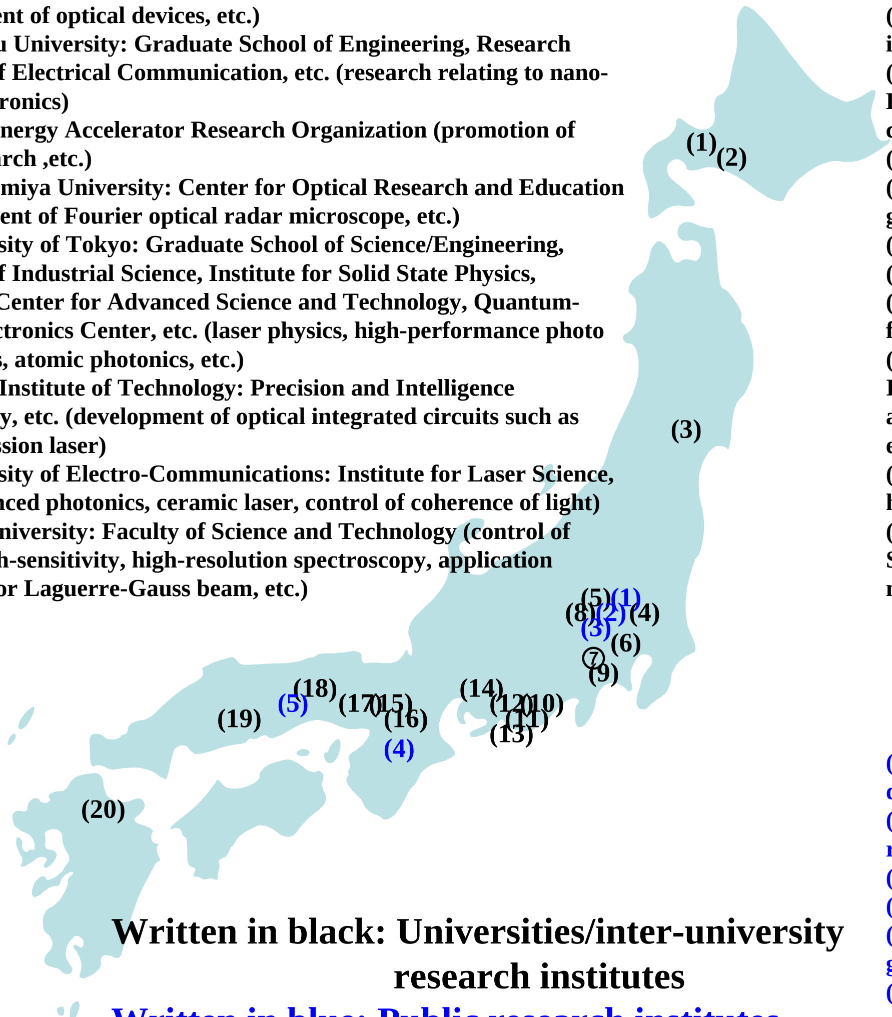
2002
○ Winners: Koichi Tanaka (Japan) and John B. Fenn (U.S.)
Reason: For their development of methods for identification and structure analyses of biological macromolecules, in particular, development of gentle desorption ionization for mass spectrometry of biological macromolecules

Examples of other innovative research/technology

○ Development of blue semiconductor laser (Shuji Nakamura)
○ Research on titanium oxide photocatalyst and research on solar light decomposition of water (Akira Fujishima)
○ Development of photonics fiber
○ Technology for measuring gravitational lens effect
○ Laser acceleration research (M. Dawson and Toshiki Tajima)
○ Millimeter/submillimeter-wave interferometric measuring technology for astronomical observation, etc.

Appendix 2: Major Research Institutes that Conduct Research in Photon Science and Technology, Focusing on Photon Source Development

(1) Hokkaido University: Research Institute for Electronic Science, etc. (research relating to nanophotonics)
(2) Chitose Institute of Science and Technology: Faculty of Photonics Science (molecular design for organic optical materials and development of optical devices, etc.)
(3) Tohoku University: Graduate School of Engineering, Research Institute of Electrical Communication, etc. (research relating to nano-photoelectronics)
(4) High Energy Accelerator Research Organization (promotion of ERL research ,etc.)
(5) Utsunomiya University: Center for Optical Research and Education (development of Fourier optical radar microscope, etc.)
(6) University of Tokyo: Graduate School of Science/Engineering, Institute of Industrial Science, Institute for Solid State Physics, Research Center for Advanced Science and Technology, Quantum-Phase Electronics Center, etc. (laser physics, high-performance photo electronics, atomic photonics, etc.)
(7) Tokyo Institute of Technology: Precision and Intelligence Laboratory, etc. (development of optical integrated circuits such as plane emission laser)
(8) University of Electro-Communications: Institute for Laser Science, etc. (advanced photonics, ceramic laser, control of coherence of light)
(9) Keio University: Faculty of Science and Technology (control of phase, high-sensitivity, high-resolution spectroscopy, application research for Laguerre-Gauss beam, etc.)



Written in black: Universities/inter-university research institutes
Written in blue: Public research institutes

(10) Shizuoka University: Research Institute of Electronics, etc. (development of mid-infrared optical devices, short pulse laser processing, etc.)
(11) Hamamatsu University School of Medicine: Photon Medical Research Center, etc. (medical application research using light photon beam)
(12) Graduate School for the Creation of New Photonics Industries (development of infrastructure technology for high-performance laser processing, etc.)
(13) Institute for Molecular Science at the National Institutes of Natural Sciences: Laser Research Center for Molecular Science, etc. (research on microchip laser, control of molecules by means of photon tools, etc.)
(14) Nagoya University: Graduate School of Engineering, etc. (lidar research, etc.)
(15) Kyoto University: Graduate School of Engineering/Science, etc. (research on generation of high-resolution quantum beam, etc.)
(16) Ritsumeikan University: Synchrotron Light Life Science Center, etc. (advanced research using synchrotron light)]
(17) Osaka University: Institute of Laser Engineering, etc. (research on laser used for nuclear fusion, etc.)
(18) University of Hyogo: Laboratory of Advanced Science and Technology for Industry (development of new light sources with use of radiation and laser and application research using these new light sources, and research for upgrading electron storage rings)
(19) Hiroshima University: Hiroshima Synchrotron Radiation Center (research on high-resolution photoelectron spectroscopy using high-intensity radiation, etc.)
(20) Kyushu University: Interdisciplinary Graduate School of Engineering Sciences, etc. (research on photoelectronic property of functional molecules/polymers, etc.)

(1) National Institute of Advanced Industrial Science and Technology (laser device development, research on extremely short pulse laser process, etc.)
(2) RIKEN: Discovery Research Institute (promotion of extreme photonics research)
(3) National Institute of Information and Communications Technology (development of quantum dot and other optical communications devices, etc.)
(4) Japan Atomic Energy Agency: Kansai Photon Science Institute (research on generation of light photon beam by means of high peak power laser, etc.)
(5) RIKEN: Harima Institute (advanced research using SPring-8 radiation)