The 21st Century Center of Excellence (COE) Program

Innovation in Coherent Optical Science

Graduate School of Electro-Communications
Department of Applied Physics and Chemistry,
Department of Information and Communication Engineering,
Department of Electronic Engineering

The University of Electro-Communications

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The University of Electro–Commnunications

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Contents

* : Group Leader

Foreword

Dr. Takashi MASUDA
President of the University of Electro-Communications

Research and education in optical science and technology at the University of Electro-Communications (UEC) has long term history, and the achievements have earned renown in the worldwide community. It is a great honor that our efforts have been highly evaluated and that the "Innovation in Coherent Optical Science" program has been chosen as a COE program of the 21st century in the category of "Mathematics, Physics and Earth Science", a core field of the natural sciences.

The alumni of UEC and graduates from the master's program are highly regarded in various aspects. The master's program is becoming very popular, and enrollment has been expanded. UEC constantly earns a high reputation from the mass media in that aspect On the other hand, our doctoral program is still considerably young and has several shortcomings. This is because it was only in 1987 that UEC was approved to launch a doctoral program. Enhancement of the doctoral program is strongly correlated with the research activity of the university. Fostering the COE program of the 21st century in our doctoral course will be a driving force to excel in our research activity.

The COE program of the 21st Century is a part of a national policy to enhance education and research activities in doctoral programs. We expect that the "Innovation in Coherent Optical Science" program will make great contributions to the enhancement of research and education in optical science and, at the same time, we also hope this will stimulate further development of the doctoral program at UEC.

Under the strong leadership of the program leader, a "Course of Coherent Optical Science" was introduced for students in the doctoral programs of three departments: Applied Physics and Chemistry, Information and Communication Engineering, and Electronic Engineering. Students with high academic achievement will be provided with financial assistance. Inspired by this program, UEC has extended the financial assistance program to the students in the doctoral program of whole University in FY2004.

The "Innovation in Coherent Optical Science" program has been smoothly administered thanks to the enthusiasm of its personnel. The first COE symposium was held in December of 2003. The university is determined to provide all the support possible to help the program win high praise from the public. Reinforcing the strength of the program and making it a distinguishing feature of UEC is in line with the basic policy of the university administration in this new era.

Currently, the "Innovation in coherent optical science" program is the only COE program to be undertaken at UEC. We are striving to further promote the "Innovation in Coherent Optical Science" program while we also endeavor to have additional programs in the fields of information and communication qualified as COE programs in the near future. Our ultimate goal is to establish UEC as a highly renowned university of science and technology worldwide.

What we expect from the COE Program

Professor **Kojiro HAGINO**
Dean, Graduate School of Electro-Communications
The University of Electro-Communications

The Japanese Ministry of Education, Culture, Sports, Science, and Technology launched the Center of Excellence Program of the 21st Century in 2002. In 2003, our "Innovation in Coherent Optical Science" project was chosen for the COE program. Under the leadership of Professor Kohzo Hakuta, our COE activities have begun at the Department of Applied Physics and Chemistry of the Graduate School of Electro-Communications in collaboration with the professors and researchers of the Departments of Information and Communication Engineering, Electronic Engineering, and the Institute for Laser Science.

The objective of the COE Program of the 21st Century is to establish leading-edge center of research and education. The "Innovation in Coherent Optical Science" project was qualified as a COE program based on the renowned research and education efforts at UEC and on our well-organized plan to create a leading-edge center. This means that our research and education activities in optical science have proven to be prominent, in light of international standards, and we have high expectations for further development. Being chosen as a COE is a great honor and pleasure to us all.

UEC aims to contribute to the field of advanced communications by pursuing new types of education and research initiatives to "develop comprehensive science and technology as well as human resources related to communication". Our program embraces basic science and applied technologies relating to innovative optical devices that are essential to the foundation of future information transfer and communications. Thus, the COE is expected to make enormous contributions to research and education efforts at UEC.

The COE will also contribute to the educational efforts in the doctoral program. For this reason, the scope of research covered by this program is wide, encompassing the three departments mentioned above so as to realize systematic education in coherent optical science in the newly launched "Course of Coherence Optical Science". At the same time, emphasis is placed upon educating next-generation international leaders in this field. Our students are encouraged to give presentation at overseas universities and institutions. In addition, foreign students are accepted into the program. COE funds will be used to employ students in the doctoral program as research assistants in the center after stringent review of their achievements and research plans. We expect that remarkable results achieved by the graduate students in this program will stimulate and inspire students in other departments. We also hope that this success will lead to a substantial increase in the number of students who enroll in the doctoral program.

The entire faculty is dedicated to supporting this COE program, and, at the same time, we endeavor to win COE designation in other fields of research. We would like to ask for your continued support and cooperation.

Prospect for the COE Program

Professor **Kohzo HAKUTA**
Program Leader
COE Program, "Innovation in Coherent Optical Science"

Our proposed program for "Innovation in Coherent Optical Science" has been chosen for the COE program of the 21st century in the category of "mathematics, physics and earth science". We embrace this appointment with great honor, expectation and responsibility. We perceive the COE program as an opportunity to add new education and research activities at UEC and we hope that receiving COE designation will call attention to the significance of the University as a venue for academic challenge and creation of culture. At the same time, we are ready to bend ourselves to the responsibility of being named a Center of Excellence for research.

"Coherent Optical Science" is a relatively new field that originated with the invention of the laser. In the past decade, however, enormous development has been achieved by blazing a trail in completely new areas such as quantum electronics, laser physics, quantum optics, nonlinear optics, and optoelectronics. Today, various methodologies established in these new areas are considered indispensable to applied sciences, such as optical processing and optical communications, and to basic sciences such as physics, chemistry and life science. The recent development of Coherent Optical Science is also noteworthy as is demonstrated by the Nobel Prizes awarded to laser cooling technology in 1997, femtosecond ultrahigh-speed phenomena in 1999, and Bose-Einstein condensation in 2001.

The UEC optical science group has been making extensive contributions to the field of "Coherent Optical Science", ranging from basic to applied science, particularly since establishment of the Institute for Laser Science in 1980. The group has been leading research activities in fields including atom optics, quantum nonlinear optics, ultra-stabilized lasers, optical interferometers, ceramic lasers, and multiply-charged ion nanoprocessing. The COE proposal derives from our future plan to promote further development of the research and education activities of the optical science group.

Activities in this program are undertaken as part of the graduate school. We hope to educate a new generation of researchers who will pioneer the frontiers of optical science through our leading-edge research.

Implementation of the COE program so as to realize the valuable educational and research benefits requires a strong commitment and innovative actions on our part. We are determined to make every effort in this endeavor. We ask for your continued support and cooperation.

Outline of the COE Program: Innovation in Coherent Optical Science

Goal of the COE Program: Creation of a Hub of "Coherent Optical Science"

Recently, great advances in optical science have had profound impacts not only on fields related to optical science, but also on other fields of physics. Researches on coherent interactions of light and matter opened a method of manipulating the quantum optical response of matter. The laser cooling/trapping method realized Bose-Einstein condensation of atoms and furthermore established a new field of atom optics that uses a matter wave as a wave medium. In addition, methods to control optical coherence keep expanding the outer limits of science with developments ranging from ultrahigh precision measurement to gravitational-wave astronomy. Moreover, coherent quantum control has produced the concept of quantum information processing, which has laid the physical foundations of new information technologies such as quantum communication and quantum computing. It should be mentioned that the rapid development of optical science has been founded on the innovation of advanced solid state laser technology in the last decade.

The goals of this program are: (1) to integrate rapidly developing areas related to optical science into one scientific discipline, "Coherent Optical Science", with the aim of developing applications in a systematic manner, and (2) to build a research and education hub where the basic science and technology of the 21st century can be nurtured. Our buzzword is "manipulation and control of coherence" of not only light but also matter. The methodology of "coherence manipulation and control" will be implemented at our hub with the aim of developing and deploying basic research, photonics, and information and communication technology.

Significance of the COE Program to UEC

To focus on "Creation of Advanced Communication Science" as the main pillar of education and research efforts in the 21st century, UEC has reorganized its Graduate School of Electro-Communications into seven departments (information and communication engineering, computer science, electronic engineering, applied physics and chemistry, mechanical engineering and intelligent systems, systems engineering, and human communication) so that education and research activities can be carried out comprehensively.

Under the COE program, "Advanced Communication Science" will be created using an interdisciplinary approach by supplementing the educational framework of these seven departments with a cross-sectional research framework that deals with materials and devices and links them with information. In other words, we believe that a traditional academic structure complemented by a research and education system designed for "Coherent Optical Science" will make a great contribution to the flexible development of "Advanced Communication Science".

Research and education in optical science at UEC have been carried out in a manner that transcends disciplinary boundaries and have achieved a remarkable record that is highly acclaimed. The Institute for Laser Science has played a leading role in this endeavor. Based on our research and educational activities in optical science, we aim to pioneer new frontiers of science through the convergence of different fields and to establish a cross-sectional framework of education at the graduate school responsible for "Advanced Communication Science".

Research Activities at UEC

Optical science group at UEC has brought prominent results in various fields of optical science over the past two decades. The achievements have been reached in such fields as atom optics, quantum nonlinear optics, Fourier interferometers, ultrahigh coherence lasers, fiber lasers, ceramic lasers, and multiply-charged ion trapping. The present COE program develops and deploys research and educational efforts based on these research activities. The basic view of the research effort is to respect and develop free-thinking by individual researchers. At the same time, researchers are encouraged to starting collaborative works crossing over the traditional disciplines. Researchers are involved in one of the three projects: creation of new functions by coherent control of light and matter; creation of new functions by ultrahigh precision control of light; and creation of new generation coherent photonic devices. The projects will adopt an interdisciplinary approach and will be deployed through collaboration of various fields including material science, device science, and low temperature science. In particular, next generation applications in the field of information and communication, such as quantum computing and quantum information, will be incorporated into our research activities. These research projects will be conducted in national and international collaborations.

Education Program at UEC

This program aims to establish UEC as a hub of research and educational activities in coherent optical science, launching a new approach to graduate school education by bringing down the walls between disciplines so as to lay a foundation for the education and training of a new generation of researchers who can meet the challenge of optical science in the 21st century.

In this program, we introduce a "Course of Coherent Optical Science" that incorporates information and communication engineering, electronic engineering, and applied physics and chemistry. In this course, students are educated in optical science and photonics in parallel with their majors. The "Course of Coherent Optical Science" is offered in the doctoral program. From the students who take this course, "COE research students" are chosen and trained as independent-minded researchers who can lead the next generation research activities in optical science. The COE research students will be provided with an environment for self-initiated research with sufficient financial assistance. Before granting a degree to a research student, evaluation and opinion will be sought from across the nation and from abroad via the Internet so that an "internationally recognized degree" is virtually guaranteed.

In this program, we constantly emphasize the full development of basic academic capabilities. In today's leading edge research efforts, deep understanding of basic science and the ability to reorganize one's understanding are prerequisite. Therefore, a perspective based on fundamental knowledge and systematic learning is essential for students and young researchers to undertake creative research activities with clear goals.

In order to carry out the program with vigor, international students are welcomed so as to facilitate an inspiring research environment. For this purpose, we intend to build relationships with foreign universities through joint research projects and would like to accept students recommended by these universities.

Manipulation of Optical Reseponse with Quantum Coherence

Department of Applied Physics and Chemistry

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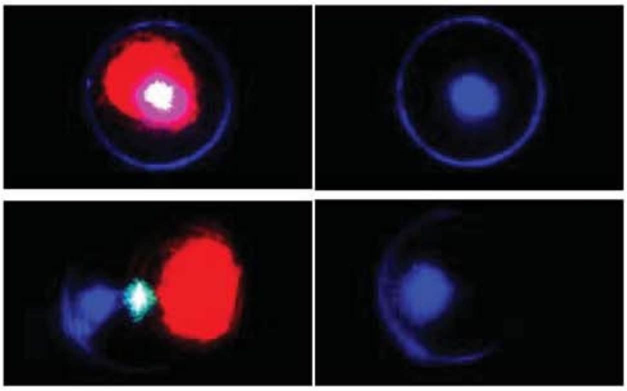
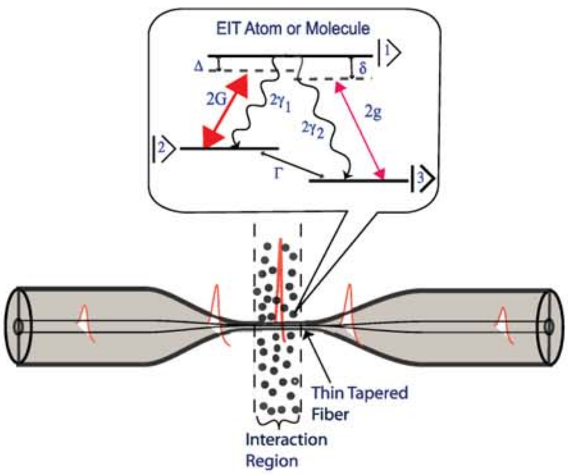
By incorporating quantum coherence in the process, optical responses can be manipulated beyond the conventional limit. We demonstrated the basic principle using atomic hydrogen. In this project, we extend the physics of quantum coherence to condensed phases. Key issue of the project is to use solid hydrogen as the medium. Solid hydrogen is a molecular crystal making up of H_2-molecules and is known as a quantum crystal.



Photographs (right) exhibit emission patterns observed for stimulated Raman scattering in solid hydrogen. Blue ring is a conventional phase-matched anti-Stokes component. Other than the blue ring, much stronger blue spot is observed. This blue spot does not satisfy the conventional phasematching, and it is a clear manifestation of the quantum coherence effect. Furthermore, using well-controlled quantum coherence in solid hydrogen, we can slow down the pulse speed of light to c/30,000 and can efficiently generate parametric sidebands even for incoherent fluorescence light.

We are exploring taper-fiber technology to apply for quantum optics. The point is to prepare a very thin part with a subwavelength diameter along the fiber. Left figure illustrates a schematic diagram. The very thin part is embedded in an optical medium. Light propagating in the fiber interacts with the medium through evanescent field in the very thin region. We can manipulate quantum coherence of the medium through the evanescent field and can control the quantum optical behaviors of the propagating light.



Atom optics

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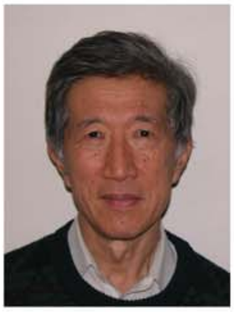
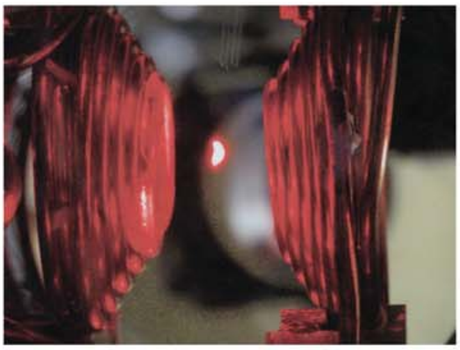
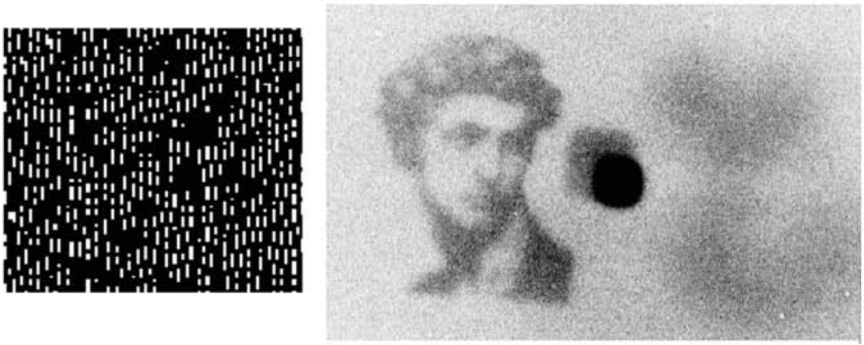


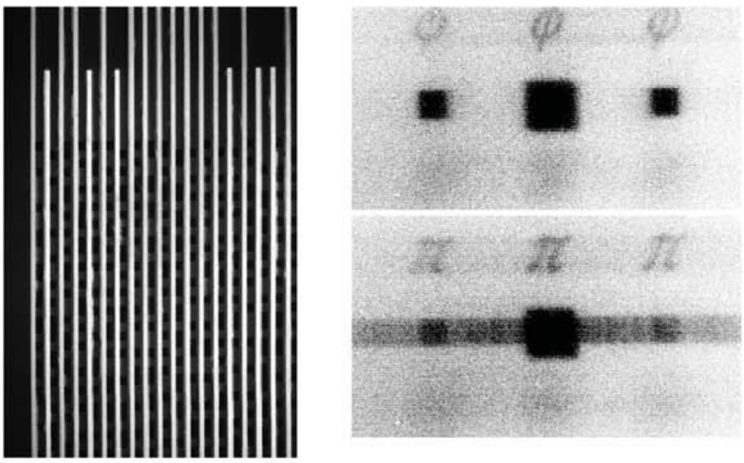


Trapping of neon atoms

The wave nature of atoms and molecules was verified experimentally more than 70 years ago. However, no one has dreamed of using the wave nature of atoms for scientific or engineering applications until recent years. The wavelength of atoms at room temperature is so short that it was extremely difficult to extract wave nature in any applications. In 1980's the technique to cool an atomic gas to ultra-low temperature has been developed. The wavelength of such ultra-low temperature atoms is close to that of optical waves, and it becomes possible to run experiments which shows a variety of wave nature, such as diffraction and interference. Figures shown on the left are holographic atomic patterns that are generated by interference of a neon atomic wave through a transmission hologram of SiN thin film (left). The atomic pattern can be electronically manipulated by embedding electrodes on the hologram (bottom figures).



Atomic wave holography. The hologram of SiN film (upper left) and reconstructed atomic pattern. (upper right). Hologram with stripes of electrodes (lower left) and switching of atomic pattern (lower right).



Theoretical analysis toward manipulation of Bose-Einstein condensates

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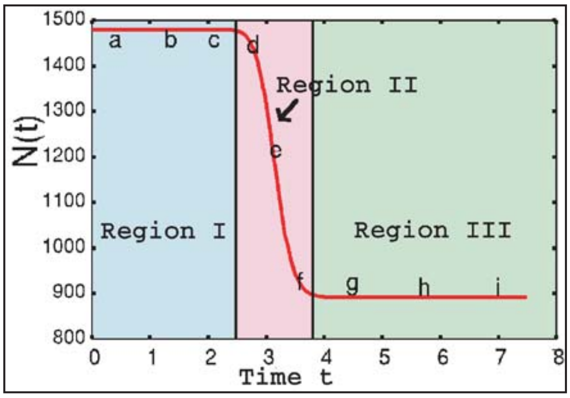
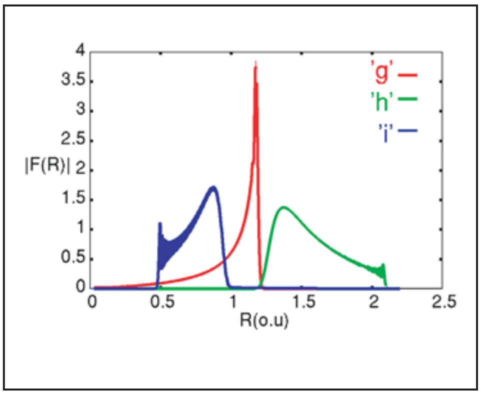
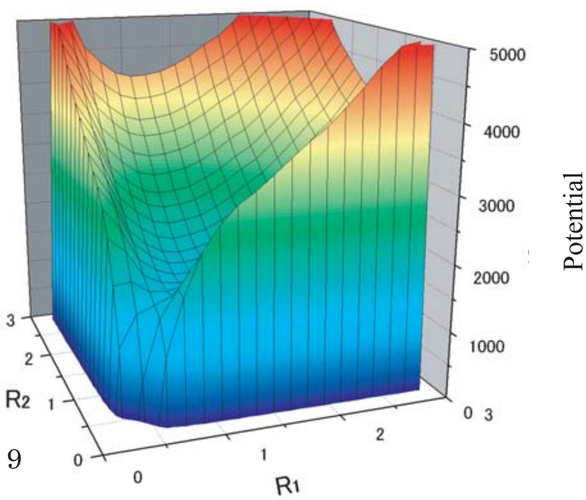




The so-called attractive BEC is formed by atoms that experience an effectively attractive two-body interaction. This type of BEC in a magneto-optical trap becomes unstable and undergoes decay when the number of atoms exceed a critical number. We visualize its transient process using the hyperspherical effective potential. The figure above on the left shows the number of atoms (abscissa) in a BEC as a function of time (ordinate). There is a decline in the number at around t=2 [oscillator unit]. On the right are snap shots of the BEC wave packet as a function of size R of the BEC. \`g', \`h', and \`i' correspond to the times indicated by the same indices.

Years passed since the dramatic demonstration of the Bose-Einstein condensation (BEC) formed of gaseous alkali atoms within a magneto-optical trap. Atom chip techniques are now developed to form and manipulate a BEC！ using electric wires that control the magnetic fields for guiding atoms. Our interest is in developing techniques for numerically analyzing the BEC properties as well as its applications.

The figure on the right is the effective hyperspherical potential surface for describing the motion of a BEC consisting of two components such that atoms in each component interact via attractive two-particle potential. The wave packet falls toward (R_1=0, R_2=0), and then leaves the trap due to recombination following a three-body collision.



Studies of Quantum Fluids and Solids

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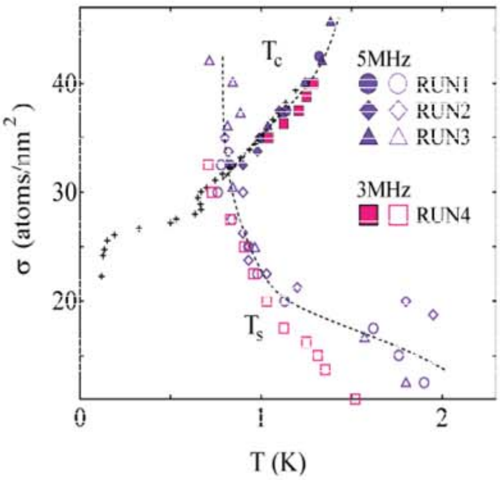
Quantum nature of condensed helium and hydrogen appears clearly because of the low mass of the atoms and the extremely weak forces between them. Our current topics are (1) the study on the nonlinear optics of solid hydrogen and (2) the interfacial friction of physisorbed helium films.

(1) The study on the nonlinear optics of solid hydrogen.
The solid hydrogen is an optical material with both a high density and a narrow line width of spectra because its molecule in solid can rotate and vibrate freely. At present, we have been developing the method of the crystal growth on the solid hydrogen. This is a joint study with Prof. Hakuta and Associate Prof. Katuragawa.

(2) The interfacial friction of physisorbed helium films.
Although the interfacial friction is a very familiar phenomenon, the mechanism on atomic scale is still an open question. We have been studying the interfacial friction of physisorbed helium films at low temperatures. This friction of the inert helium films shows a peculiar feature that the frictional force decreases drastically with decreasing temperature. This temperature dependence can be explained by the pinning of thermally activated excitations of the films. The understanding of the friction on atomic scale is important to open the possibility of controlling the friction.



Slip temperature Ts and superfuid onset temperature Tc of helium films physisorbed on grafoil. The frictional force decreases below Ts.

Coherent atom optics with ultra cold atoms

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Recent developments in laser cooling and Bose-Einstein condensation of atoms have opened up a new research field so called coherent atom optics which treat ultra cold atoms as coherent matter waves like laser light. We are interested in the manipulation of ultra cold atoms and their applications to precision measurements and quantum information processing. We have realized a Bose-Einstein condensation of rubidium (Rb) atoms (Fig. 1). Thus we can use these condensate atoms as a coherent matter wave source or an atom laser for various atom optics experiments such as an atomic interferometry and an atom holography. These condensate atoms can also be guided and manipulated in an atomic waveguide on a substrate so called an atom chip (Fig.2). Using this atom chip, we will realize a micro integrated atom circuit and it will be useful for the realization of a quantum information processing with cold atoms.

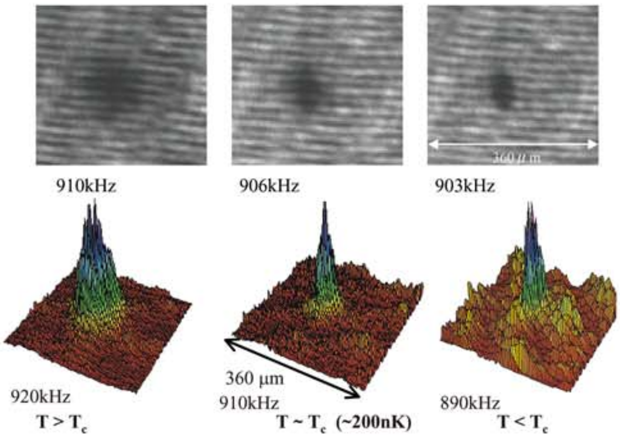

Fig.1 Bose-Einstein condensation of Rb atoms. Below a critical temperature (T_c), a narrow peak appears in the velocity distribution of atoms.

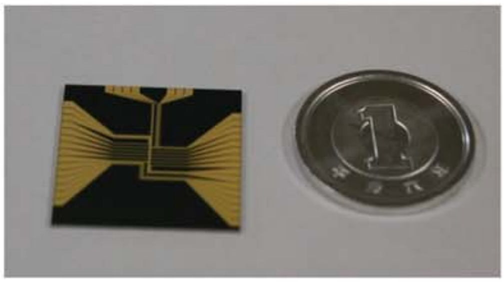

Fig.2 Atom chip (micro integrated atom circuit). Gold wires are fabricated on a Si substrate. Magnetic waveguide potentials for cold atoms can be generated by flowing current through wires.

Towards the Physical Realization of Quantum Computers

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1. Overview

In 1985, David Deutsch introduced quantum Turing machines (QTMs for short) as Turing machines which can perform so called quantum parallel computations. Then, in 1994, Peter Shor showed that QTM can factor integers with arbitrary small error probability in polynomial time. Since it is widely believed that any deterministic Turing machines cannot factor integers in polynomial time, it is very likely that QTM is an essentially new model of computation.

2. NMR Quantum Computation

Until now, many researchers have been studying how to physically implement quantum computers based on QTM. Among others, NMR (Nuclear Magnetic Resonance) offers an appealing prospect for implementation of quantum computers because of a number of reasons. But, quantum computation performed on NMR is slightly different from those performed on QTMs. So, we first developed a theory of bulk quantum computation including NMR quantum computation. For this purpose, we introduced bulk quantum Turing machine (BQTM for short) as a model of bulk quantum computation.

3. Quantum Neural Networks

Recently, in the field of theory of quantum computation, various kinds of quantum neural networks are proposed. But, it seemed that most of them are not reasonable models of quantum computations. Thus, we also proposed a quantum threshold gate as a basic component of our quantum neural network model. Then, we showed that the circuits which consist of these quantum threshold gates can be simulated by ordinary QTMs. Therefore, we can conclude that our quantum neural network model is a reasonable model of quantum computation. Then, we showed that the EXOR function can be learned by a one layer quantum perceptron by using BQTM. It is well known that the EXOR function cannot be learned by a one layer ordinary perceptron. Furthermore, we obtained some other results on the general computational capabilities of our quantum neural networks.

Mesoscopic Josephson Junctions
-- application of their coherence and charging effect

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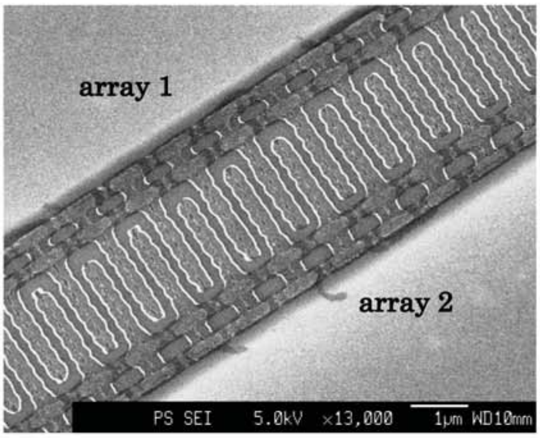

Fig. 1 Capacitively coupled arrays of small Josephson junctions. Each array is composed of serially connected parallel two-junctions pairs.

In my group quantum transport phenomena of electrons in mesoscopic systems are studied.

One of the recent topics is a quantum current mirror effect in capacitively coupled arrays of small Josephson junctions (Fig. 1). In such a device a dc current in one array is accurately copied in the other array although both arrays are only capacitively coupled (Fig. 2). This phenomenon is thought of as a combined effect of the coherence in superconductivity and the charging associated with the Cooper pairs tunneling.

We investigate the physical origin of this phenomenon and pursue its metrological applications.

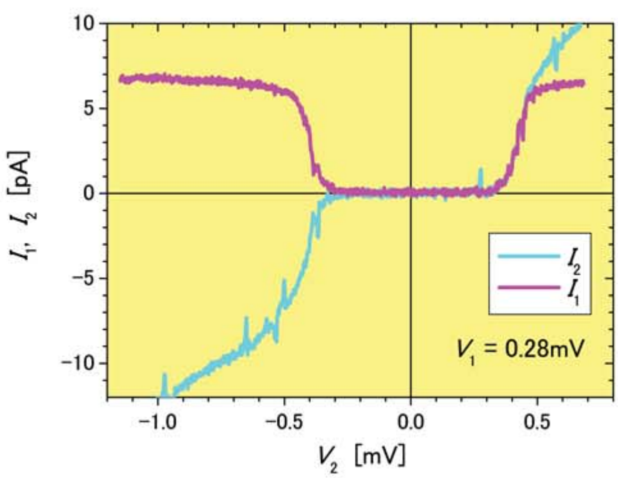

Fig. 2 Quantum current mirror effect.
In the threshold region around $V_2 = \pm 0.4$ mV of the I_2-V_2 characteristic, I_1 grows to the same magnitude as I_2, although the voltage, V_1, on the array 1 is fixed in the Coulomb blockade range.

Control and Synthesis of 3-D Spatial Coherence Function of Optical Fields with Applications to Photonic Sensing and Metrology

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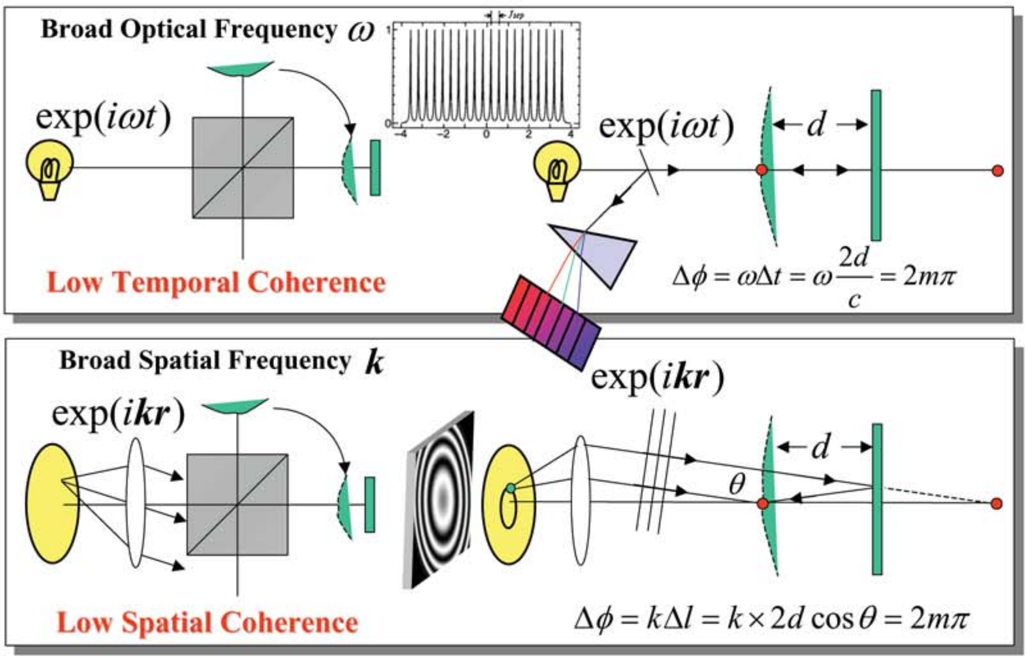
Existing techniques of OCT (optical coherence tomography) and low coherence interferometry are all based on the temporal coherence characteristic of broadband light. Shown in the top figure below is a schematic illustration of OCT that uses an optical frequency comb as a tunable light source. By changing the comb frequency interval, one can generate a high temporal coherence peak at the desired location of image sectioning. However, because of the broadband spectrum of the source, these techniques suffer from a dispersion problem in many practical applications such as biological applications, where dispersion of the object and/or the light propagation medium is unavoidable.

Synthesis of Spatial Coherence



We are developing a new technique of OCT and profilometry that is based on spatial coherence, rather than temporal coherence. Instead of a point source with a broad spectrum, an extended source with a narrow spectrum is used in our technique. We synthesize a desired longitudinal coherence function by controlling the spatial structure of an extended quasi-monochromatic spatially incoherent light source with SLM (spatial light modulator). In our scheme, the optical frequency comb is replaced with a spatial frequency chirped comb generated by a zone-plate-like source. Besides solving the dispersion problem, the technique opens up a new possibility of OCT through an extremely narrow spectral absorption window, and enables a fast longitudinal coherence scan and phase shift with SLM without mechanical moving components.

Photonic Network with Optical Burst Processing and Super-multi WDM

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Proposed architecture of Burst Photonic Networks is possible to resolve the granularity issue on WDM (Wavelength Division Multiplexing) wavelength path networks. The fundamental structure consists of two tiers of networks, which are a regional network and a long distance network. The regional network is a ring network whose edge nodes are based on optical burst processing, and the long distance networks are based on a WDM wavelength path. At the edge nodes, packets toward the same destination are aggregated into high-speed optical burst data and switched into a particular wavelength path connecting between regional networks through a long distance network.

The SWDM (Super-multi Wave- length Division Multiplexing) with more than 1,000 wavelength has a lot of possibilities for future broadband Internet. The optical source using a Raman Super Continuum and a wide-range wavelength conversion are key techniques to realize the photonic networks based on the SWDM.

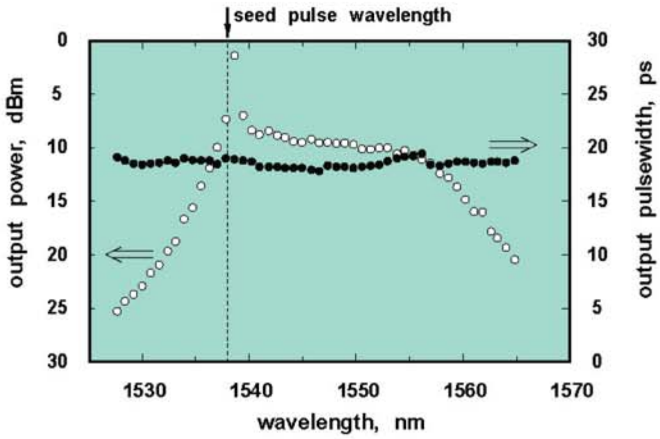

Fig.1 Raman Super Continuum Optical Source

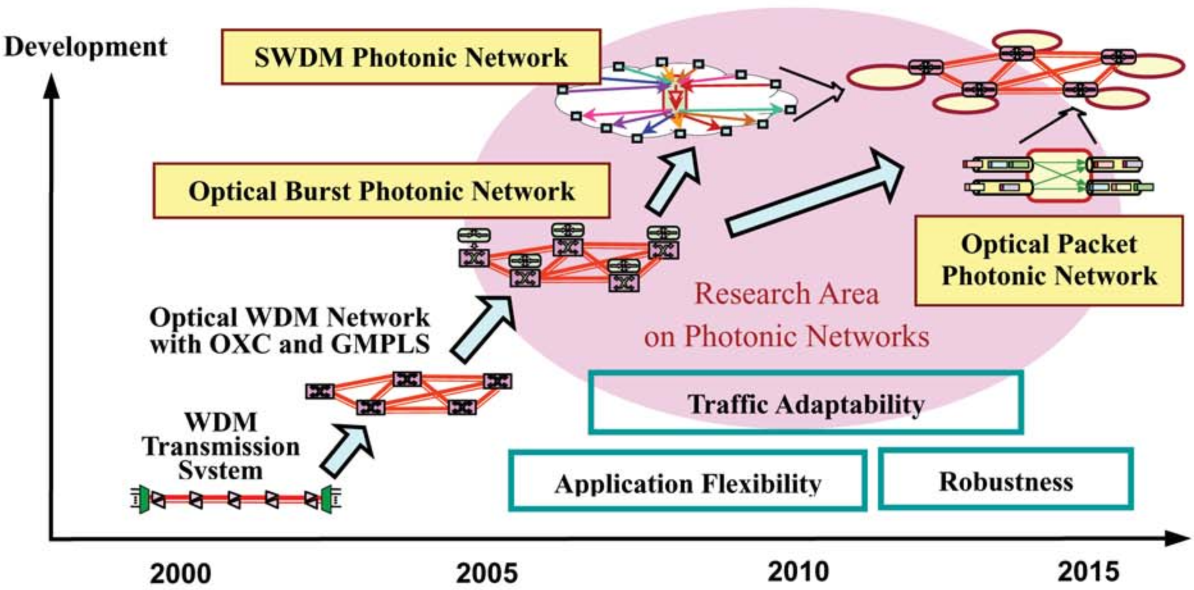

Fig.2 Photonic Network Development

Organic-inorganic nanocomposites as photonic recording media

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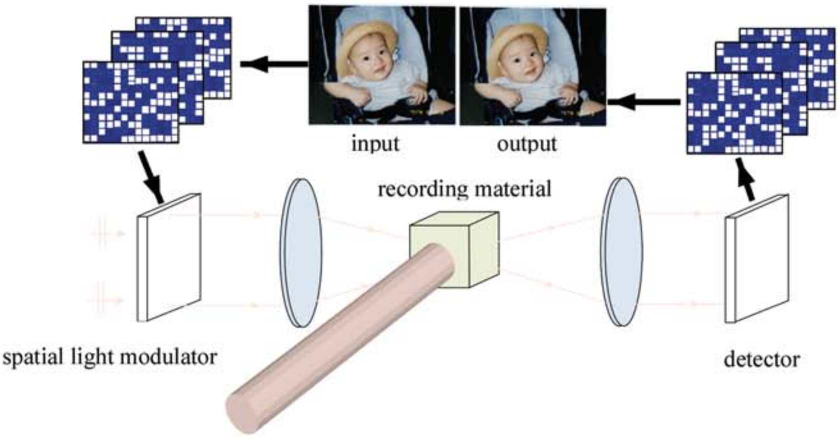
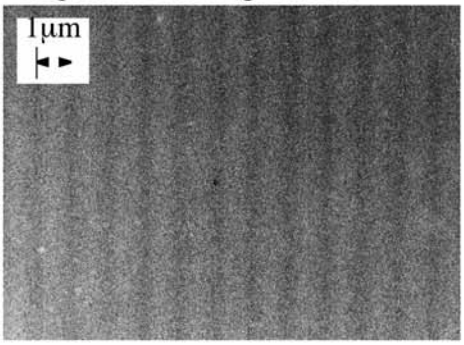


Digital holographic memory system

Methods being capable of recording temporal and/or spatial information embedded in coherent optical waves have received much attention owing to ever-increasing demands for more efficient and much denser information handling capabilities. Volume holographic memories (called holographic data storage systems: HDS) store optical wavefronts as 3D information in space and have been phenomenal in the last ten years owing to their ultrahigh storage capacity and ultrafast access speed with parallel recording/readout.

TEM image of holographically induced periodic distribution of SiO_2 nanoparticles



To realize HDS, we need photonic recording media possessing high recording sensitivity and dynamic range (high-contrast refractive index changes). To meet these requirements, we have developed novel organic-inorganic nanocomposite photopolymers being capable of permanent volume holographic storage with high diffraction efficiency and high dimensional stability. This photopolymer system also opens a possibility of creating completely new photonic materials such as linear and nonlinear photonic crystals.

Coherently additive THz diamond emitters and their applications

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The aim of this research is to develop a high power Terahertz (THz) radiation source using a diamond photoconductive device. The objectives is to open a new field of nonlinear optics in THz frequency range. THz radiation covers the frequency range between 100 GHz and 10 THz (i.e. a wavelength between 3 mm and 30 μm), which spans the spectral interval between the microwave- and the infrared regions of the electromagnetic spectrum.

Emission from a photoconductive antenna driven by an ultra-short-pulse laser is one of most powerful sources in this region (Fig.1). The emission density on the emitter is limited by the shielding of the applied electric field due to the generated THz electric field. The near-field THz electric field E_{THz} is given by $E_{\mathrm{THz}} = -E_b \dfrac{\sigma_s \eta_0}{\sigma_s \eta_0 + (1+\sqrt{\varepsilon_r})}$, where ε_b is the applied electric field η_0 is the free-space impedance, ε_r is the relative dielectric constant of the semiconductor substrate, and σ_s is surface photoconductivity. This equation implies that the emitted radiation should saturate at $E_{\mathrm{THz}} \approx E_b / (2+\sqrt{\varepsilon_r})$. Therefore, the application of a higher electric field on the gap is the only way to generate higher power radiation. That is reason why we use a diamond as a photoconductive material.

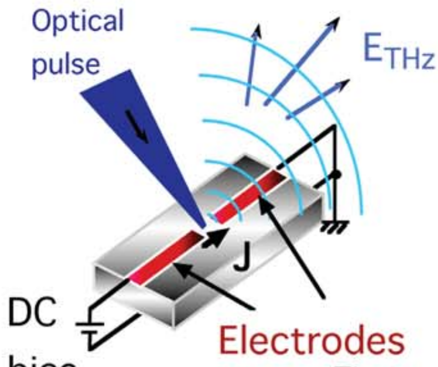

Fig.1

To date, a 2-kV DC voltage can be applied to the 10-μm PCD gap with an over-coated layer for keeping sufficiently high dark-current resistivity. This electric field strength is two orders of magnitude larger than that of conventional GaAs emitters. We produced high energy density (10μJ/cm^2) THz emission by inducing coherently-additive emission from more than 2000 photoconductive emitters using an ultra-short pulse Kr*F laser (Fig.2).

To produce higher power THz radiation, we are developing a system having angular multiplexing for the pumping laser pulses and electrical pulse stacking for the applied electric field on the emitters. In this system, intense coherently-additive THz emission will be obtained with incoherent laser driving pulses.

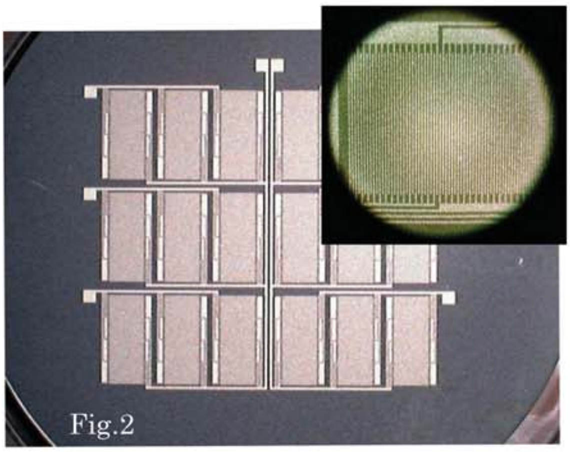
Fig.2

All-optical ultrafast pulse recording/regeneration

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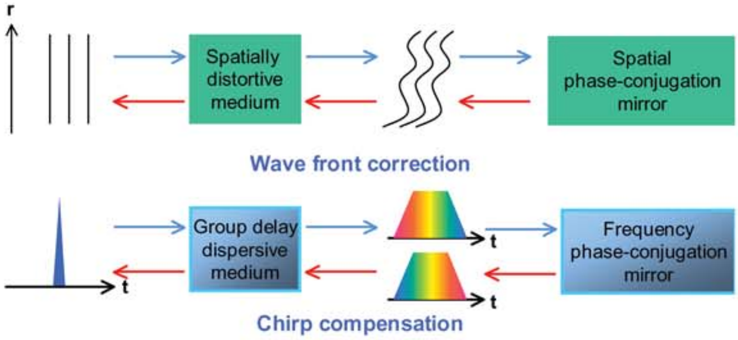
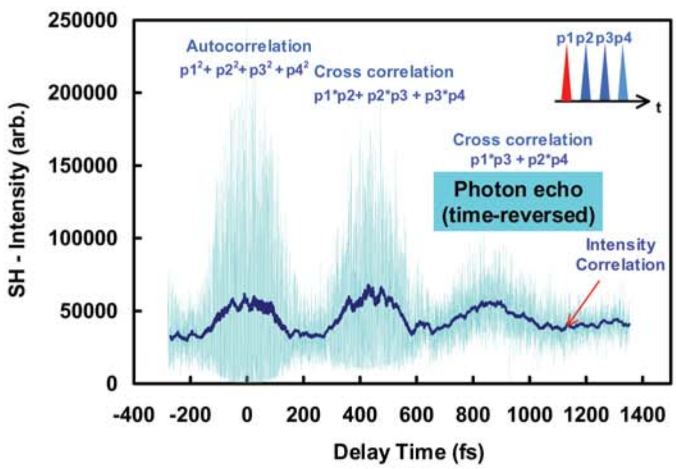


Difference between spatial and frequency domain phase-conjugation mirrors.

Because of broad spectrum, an ultrashort pulse changes its temporal phase structure due to Group-Delay-Dispersion (GDD). The frequency-domain phase-conjugation mirror generates a time-reversed replica of the initial pulse shape after pass through again the same GDD medium.

A femtosecond time-reversed replica generated by time to frequency transformation.



As well known as the photon-echo system, time-reversal operation requires frequency resolved coherent interaction to resonant matters. Introducing nonlinear coherence transformation techniques (frequency to time or frequency to spatial frequency), the time-reversal operation has been demonstrated in a nonresonant medium such as a piece of glasses. The frequency multiplexed nonlinear optics is effective for pulse-to-pulse coherent summation including WDM optical memories and phase-sensitive optical encoder/decoder.

Ultrahigh-Frequency Short Pulse Generation based on All-Optical Semiconductor Gating

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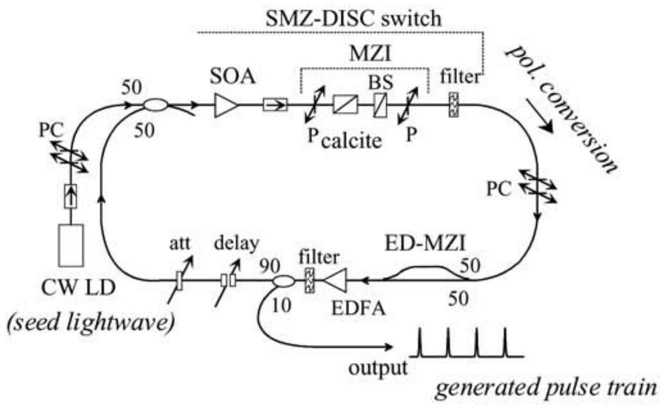
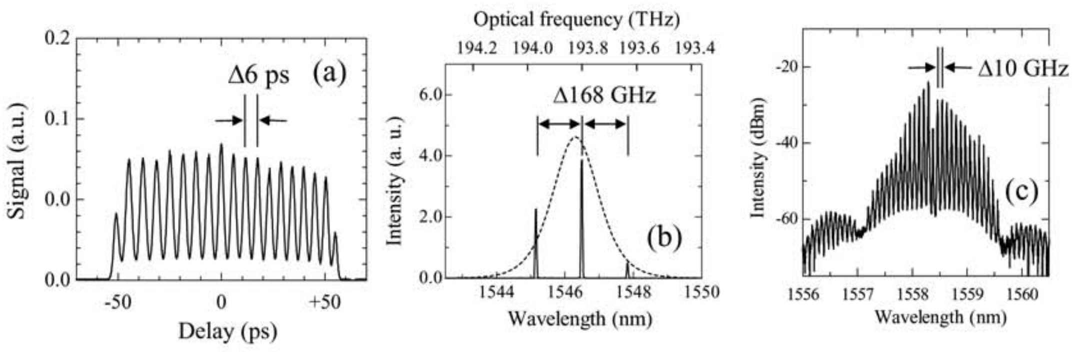


DISC-Loop-type ring oscillator

We have been exploring ultrahigh-frequency, short pulse generation based on a new nonlinear optical mechanism, which differs significantly from the conventional mode-locking, and its high-precision control techniques. As has originally been proposed by this author and his coworkers in 2000-2001, the optical center frequency, the pulse width, and the repetition frequency of the generated pulse train are *independently* controllable, respectively, by tuning the optical frequency of the seed cw light, the timing width of the all-optical semiconductor gate (DISC), and the harmonic cavity frequency of the oscillator, in principle.



(a), (b): 1.5-ps, 168-GHz DISC-gating window shape and its Fourier-transformed spectrum*)

(c): Optical-comb spectrum from the 5-ps, 10-GHz pulse generation (Y. Ueno et al., Appl. Phys. Lett., 2001)*)

*) observed by the present author and his coworkers at NEC Corp., Tsukuba.

To date, a 10-GHz, 5-ps pulse train has been observed (Fig. (c)). Regarding the DISC-type all-optical gate that was separately proposed by this author and his coworkers, a 168-GHz, 1.5-ps-wide gate window has been demonstrated. The DISC-loop-oscillator mechanism will offer a brand-new option in the fields of high-precision optical metrology.

Manipulation of light and matter on the basis of driving maximal coherence

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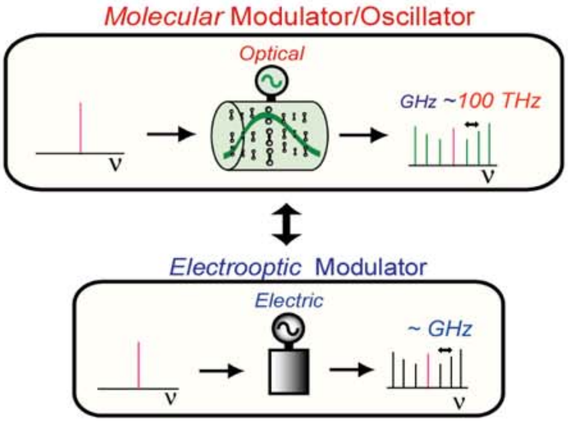
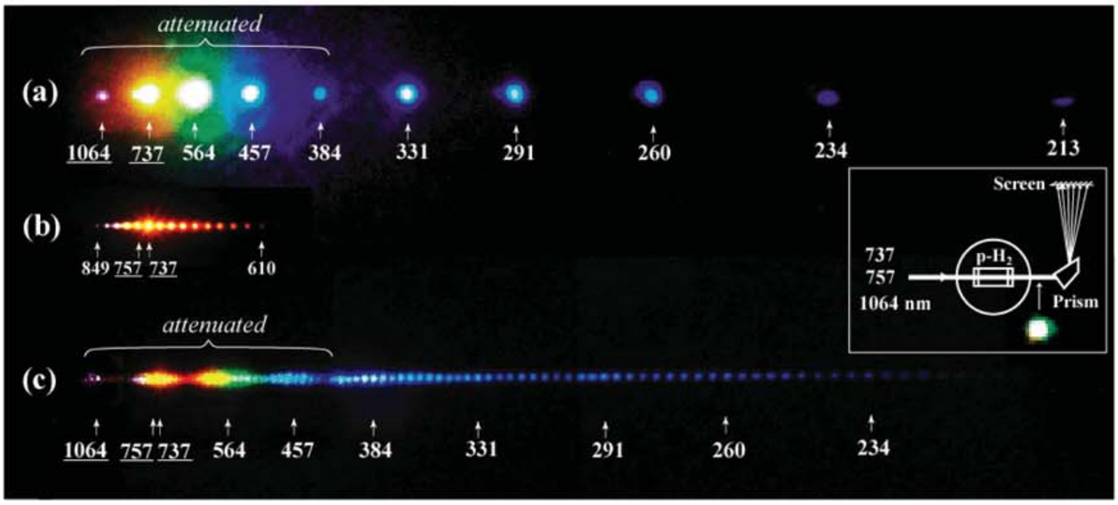


We have realized that by driving Raman processes adiabatically a high density molecular ensemble (~10^{20} cm^{-3}) can be made to coherently vibrate and/or rotate. Such a molecular ensemble can be applied to a light modulator at ultra-high frequencies of ~ GHz ~ 100 THz.

The photograph below shows sideband spectra obtained by modulating single-frequency laser radiation with coherent molecular oscillations, which are adiabatically driven at near-maximal coherence in molecular hydrogen with densities of ~10^{20} cm^{-3}. The modulation frequencies are (a) 125 THz, (b) 10 THz and (c) both 10 and 125 THz.



All of the sideband radiations are of a high quality as an actual coherent light source over infrared to near vacuum-ultraviolet wavelengths. We believe this process to be applied as a novel ultra-short pulse laser using these light sources, in which center frequencies and repetition rates are widely tunable.

We study various optical processes on the basis of adiabatic production of quantum coherence and their applications to manipulating light-matter interactions.

Ceramic Lasers Developed by Nano-Technology

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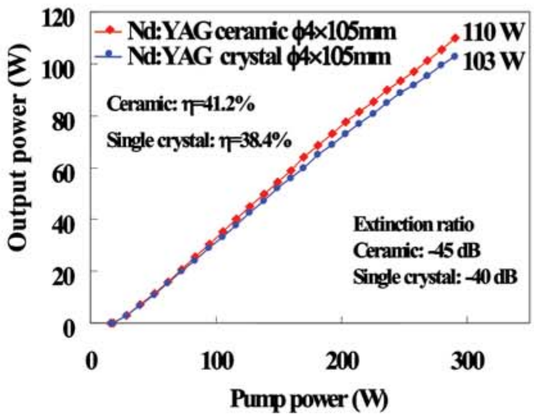
We developed ultimately transparent "scalable laser quality ceramics" using modern ceramic technology. Laser quality ceramics have been a dream of solid state lasers for a long time. We are proud because this is a real revolutional technique for solid state lasers.

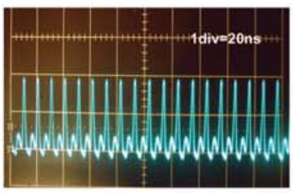


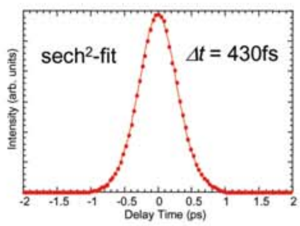
Ceramic YAG is better.

Nano-crystalline particles made by the liquid phase chemical reaction grow to the fully transparent ceramic laser materials through the vacuum sintering process. Solid state crystal growth is quite popular in our nature and gives us another possibilty to make glass-like fabricated crystalline materials. The high quality ceramics YAG is comparable to or even better than single crystal YAG. Ceramic YAG lasers demonstrated more than kW output and 60% optical-to-optical efficiency. The biggest advantage is the scaling to the meter-size plate. As a result, the ceramic laser is the most promising active medium for the laser fusion drivers.

Ceramic Y_2O_3 laser generated 430fs Fourier-limited pulses in the SESAM mode locking as shown in Figures. Sesquioxide ceramic lasers are most promising for the femto-second lasers for industry.

We are developing world original technology for solid state lasers. It makes possible to design the crystalline material by the modern ceramic technology.





Pulse train and auto-correlation trace.

Nano-technology with highly charged ions

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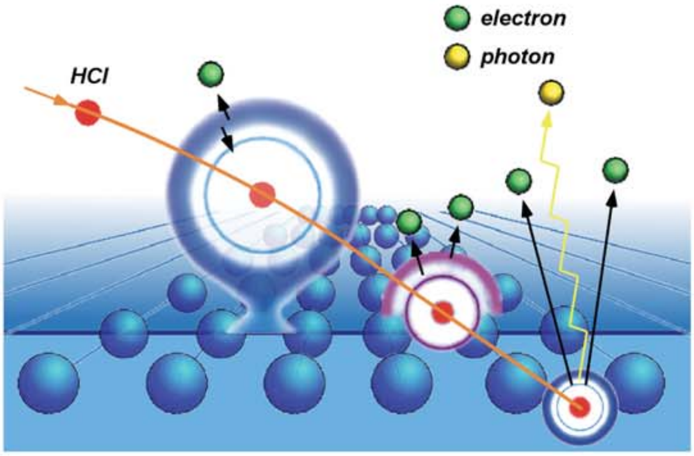
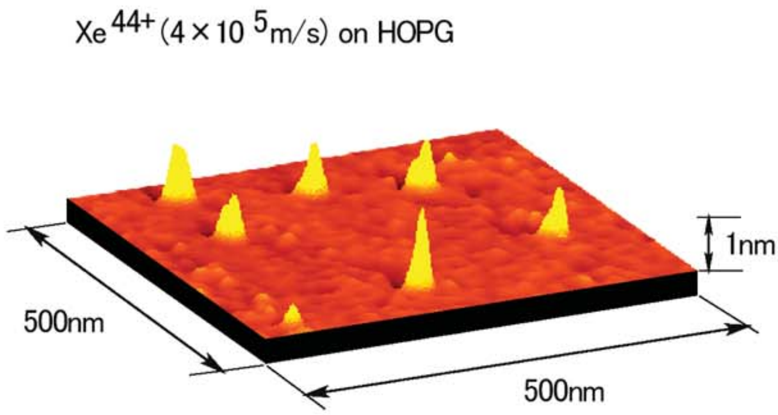


Left: Interaction of an HCI with a solid surface. The huge potential energy of a HCI induces nano-scale modification on a surface.

Highly charged ions (HCIs) have potential energy as huge as several tens to several hundreds keV while its size is smaller than atomic size. Thus HCIs can induce dramatic changes in the physical properties in a nano-scale area of the surface.



Right: STM (scanning tunneling microscope) image of highly oriented pyrolytic graphite (HOPG) irradiated with Xe^{44+} ions. Each protrusion was produced with single ion impact.

Our goal is to produce a new device such as photonic crystals by arranging HCI-induced nano-structure into arrays. In Institute for Laser Science, pioneering work with one of the world's highest performance HCI source, the Tokyo EBIT, has been being performed.

Synthesis of nanometer-sized semiconductors and basic characterization for their applications to optical energy conversion devices

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Semiconductor particles with sizes of an order of a few nanometers are called semiconductor quantum dots (QDs). The sizes are larger than the lattice constants but comparable to the spatial extension of the wavefunctions of excitons, electrons, or holes on the corresponding bulk materials. Consequently, the quantum confinement effect occurs and they have new interesting physical and chemical properties completely different from those of bulk materials. Hence, research on semiconductor QDs is developing into a large interdisciplinary field. Owing to the quantum confinement effect, they show the size-dependent optical properties in particular, such as optical absorption, photoluminescence (PL), and large optical nonlinear properties. Thus, they have potentials and promises both for the basic study of the three-dimensional confinement in semiconductors and for the applications in the field of optoelectronic devices. We are investigating the optimal synthesis conditions for their applications to optical energy conversion devices and characterizing the relation between relaxation processes (radiative and nonradiative) and optical energy conversion in semiconductor QDs together with the steady state characterization for the following topics:

(1) Nanostructured oxide semiconductors such as TiO_2 and composite of ZnO and SnO_2 which are promising candidates for photoanode materials applied to solar cell fabrications. Optical absorption prospects are increasing with depositing oxide semiconductors in a nanometer-sized structure that offers a large surface area.

(2) Oxide semiconductors have low solar energy conversion efficiency because of their wide band gaps. For solar cell application, organic dye sensitization is one of the methods used to extend the photoresponse of the electrodes to the visible region. In addition to organic dyes, narrow band gap semidonductor QDs, such as CdS, CdSe, and PbS, have attracted significant interest as light harvesters in solar cells. We are investigating the effects of nanostructure of the electrodes sensitized with semiconductor QDs on optical absorption, photocurrent properties, optical energy conversion, and relaxation processes in order to get the optimal conditions for solar cell fabrications.

(3) ZnS QDs doped with transition metal ions, such as Mn^{2+}, have attracted much attention in the past few years due to the change in their optical properties in accordance with the quantum confinement effect. They form a new class of luminescent materials because of the high fluorescence quantum efficiency (~18%) compared with bulk materials. We are investigating the effects of surface passivators and ultraviolet irradiation in order to achieve the increase of fluorescence quantum efficiencies together with radiative and nonradiative relaxation processes.

Monitoring and Control of Epitaxial Growth by Optical Reflectance

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Electronic and optical devices using compound semiconductors such as GaAs and GaN consist of thin-layered structures fabricated by the epitaxial growth. Practical devices of two-dimensional electron gas FETs and quantum-well lasers are grown by Metal Organic Vapor Phase Epitaxy (MOVPE) having an ability of precise control of the layer thickness and the composition of the layer material. Recent progress in quantum devices requires a strict control of the growth. For example, in the growth of quantum dots (QDs), the control of not only their size in nm-scale but also of their density are indispensably required to avoid a subband-level fluctuation and to control the quantum correlation between dots. For this purpose, in-situ observation of the surface during growth enables to measure the dot size and density.

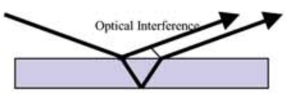
Optical reflectance is an effective method of monitoring the surface in the vapor phase epitaxy, instead of the electron probe used in the vacuum. Up to now, we succeeded in the monitoring of the decomposition process of organometallic molecules on the surface and the chemical stoichiometry of the surface during growth. Recently we try to clarify the surface process in GaN MOVPE, which is a large lattice-mismatched growth, and to characterize the surface roughness related to the dot size and density in real time by using the optical reflectance monitoring.

Characteristics of optical reflectance and the surface information

Optical Interference

Optical interference between the substrate/epilayer interface and the surface. Reflectance oscillation is observed.

Layer thickness and the growth-rate Is monitored by the oscillation period.



Optical Interference
-Thickness Monitoring

Rayleigh Scattering

Surface roughness smaller than the wavelength of the monitoring light can be detected. Shorter wavelength and shallower incidence become more sensitive to the surface roughness.

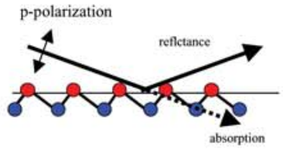
Dot size and density

Rayleigh Scattering
-Roughness smaller than optical wavelength

Surface Photoabsorption

Incidence at the Brewster angle becomes sensitive to the surface dielectric change

Detection of submonolayer coverage and surface stoichiometry



Surface PhotoAbsorption
-Surface stoichiometry

Device Applications of Silicon-Related Nanoparticles

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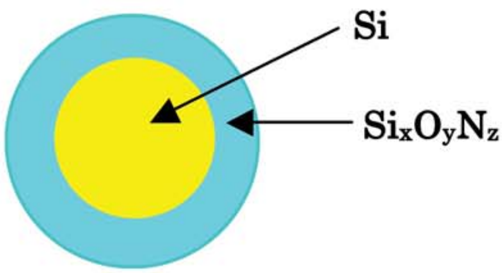
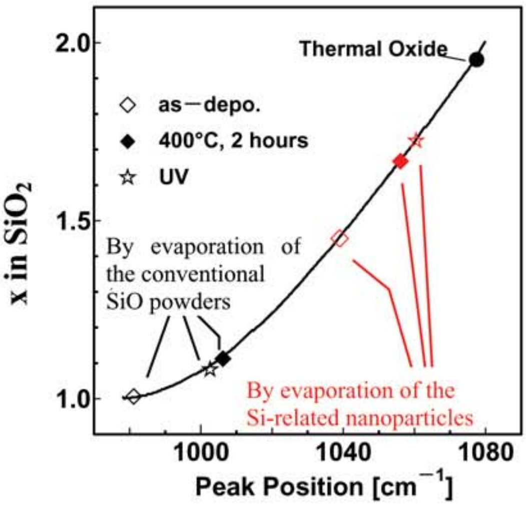
Silicon-related nanoparticles refer to silicon (Si) nanocrystals surrounded by SiO_2 or Si_3N_4, as shown right. Here, the Si nanocrystals are crystalline Si particles with a size in the order of 10^{-9} m. The Si nanocrystals in the Si-related nanoparticles are ideal quantum dots with a stable surface, where carriers (electrons and holes) and phonons are to be confined.



Silicon-Related Nanoparticle

The physical properties unique to silicon quantum dots make Si more attractive as a material of optoelectronic and functional devices. The sizes of Si quantum dots can be precisely controlled by their interaction with coherent light causing so-called photo-oxidation.

The average size of the Si nanocrystals is determined to be 2 nm from the phonon confinement in the Raman spectrum. A good-quality of SiO_x film was obtained by evaporating the Si-related nanoparticles in vacuum and photo-oxidizing the deposited film. In the right figure showing the peak wave numbers in Fourier Transform of Infrared Absorption (FTIR) spectra of various silicon oxides, x in SiO_x obtained from the Si-related nanoparticles is close to 2, suggesting oxide with a quality as good as thermal oxide's. This achievement is to be well appreciated in the Si VLSI and other device technologies, because it realizes low-temperature deposition of high-quality oxide, which could not be achieved by evaporation of the conventional SiO powders.



Oxide Quality by FTIR

We will further explore electrical and optical properties unique to the Si-related nanoparticles for novel devices.

Theoretical study of optical properties of Nano-scale systems

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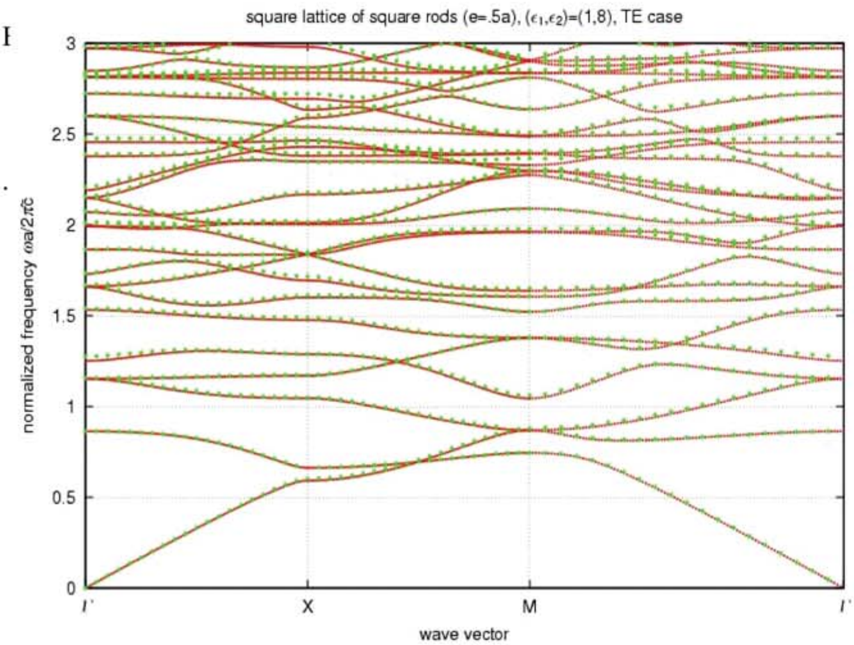
We are studying the optical properties of nano-scale systems theoretically. Though my main interest is in those of size-quantized systems, which show non-local responses, reflecting the coherence of the wave functions of matter, we are also doing the calculation of the photonic bands with high accuracy. In addition to an improved plane wave method (inverse matrix method) which we have developed for a decade, we have also started the photonic band calculations by the finite-difference time-domain method. So we are always able to confirm the accuracy of our calculations. We are next going to investigate the physics of photonic crystals with non-linear media, the control of the optical properties of nano-scale systems embedded in photonic crystals, and so on.



Example of comparison of the results by improved PW and FD-TD methods.

Development of Molecule-Based Photonic Devices

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Chemists can synthesize molecules as they design and analyze their physical and chemical properties at the single molecular level. Many researchers in the materials chemistry think, however, that construction of supramolecular architectures in solids is very important, since the symmetry and periodic nature of the crystals are essential for bulk conducting/magnetic/photonic materials. We assume that crystals could be prepared from molecules, just like molecules from atoms, according to the crystal-design or crystal-engineering techniques, but difficulties have often been claimed in applying usually weak intermolecular interactions to the control of mutual geometries between molecules.

We have developed various molecule-based magnetic materials. Self-assemblies of transition-metal ions and bridging ligands have afforded fruitful results, owing to the coordination bonds possessing strong directive characters for both donating sites in ligands and accepting sites in metal ions. Among such metal-assembled complexes, we are now studying magnets switchable by external stimuli, e.g. photo-irradiation. Figure 1 shows an example of photo-induced magnetization on a basically antiferromagnetic complex solid. One of the advantages of molecule-based magnets is optical transparency. Figure 2 depicts the crystal structure of a chiral magnet. The magneto-chiral dichromism (MChD) has been of current interest toward novel multi-functional materials.

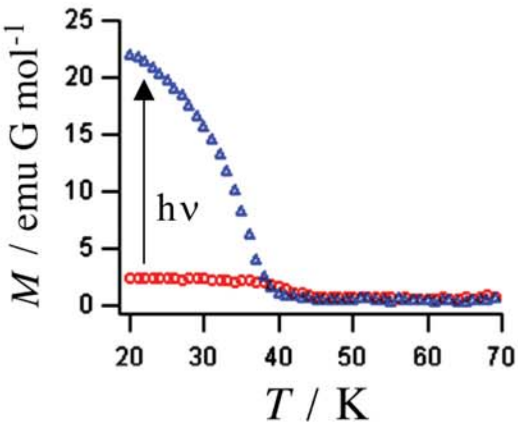

Figure 1. Photo-induced magnetization of a $[Fe(N_3)_2(pyrimidine)]$-based antiferromagnet with T_N = 39 K.

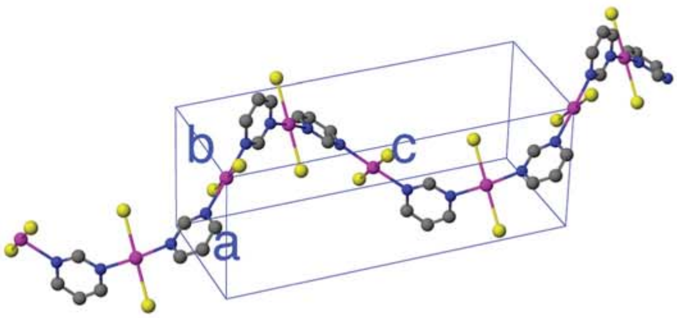

Figure 2. $[MCl_2(pm)]$ moiety with a 4_1 screw symmetry in the crystal of $[MCl_2(pm)_2]$ (M = Fe, Co; pm = pyrimidine). They were characterized as weak ferromagnets below 6.4 and 4.5 K for M = Fe and Co, respectively.

Optical properties of semiconductor quamtum structures for optoelectronic devices

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We are studying the optical properties of semiconductor quantum structures for future optoelectronic devices. Zero-dimensional quantum dots and other structures are investigated.

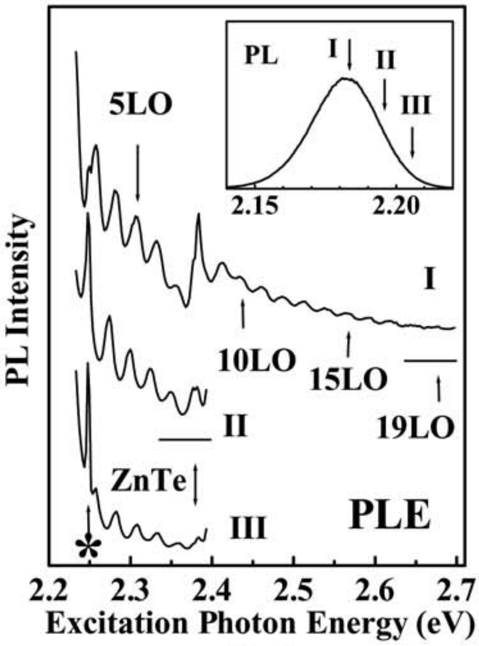


Fig. 1

Understanding of carrier dynamics in quantum structures is essential for the application to ultrafast electronic or bright and fast optical devices. Figure 1 shows photoluminescence excitation spectra of CdTe quantum dots. The 19th order optical phonon structure is observed, and is the highest one among the reported material systems so far including bulk, quantum wells, and dots. This indicates fast exciton relaxation from matrix to dots, as well as strong carrier confinement and strong electron-phonon coupling in quantum dots.

Direct observation of temporal photoresponse is performed in low-temperature grown GaAs film. Results of the pump-probe measurements using double-pulses are shown in Figure 2. Because of the suppression of the slow tail component, no pattern effect is recognized for the separations of 7.6 and 10 ps. The feasibility of high repetition switching more than 100 GHz is demonstrated.

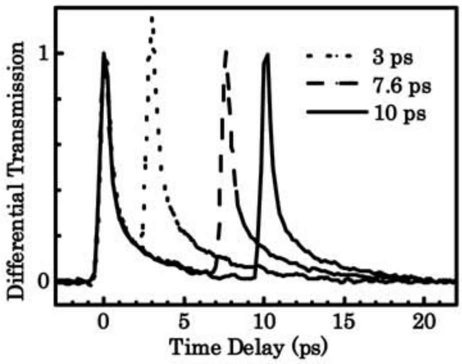
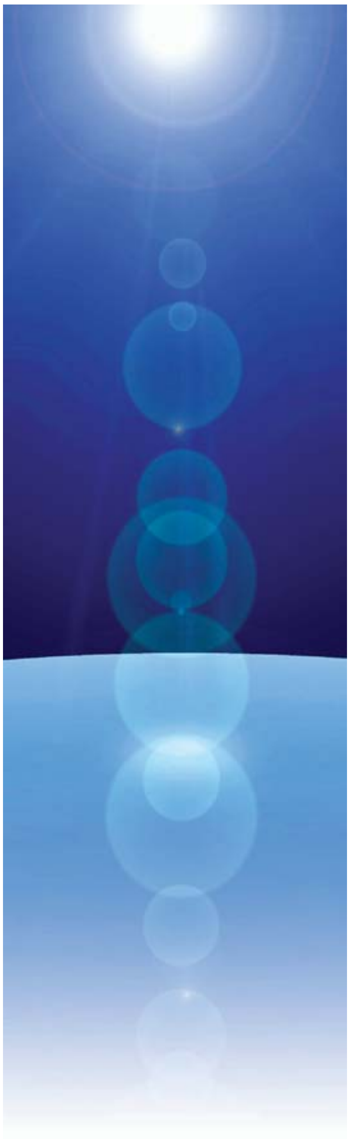


Fig. 2

For all-optical switches necessary for high bit rate optical communication, optical nonlinear properties of semiconductor quantum structures having large nonlinearity and fast photoresponse are explored. In order to realize efficient light sources or new optical phenomena, research on interaction between optical centers and nanometer-scale matrices is initiated.



The University of Electro-Communications
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Innovation in Coherent Optical Science

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