Grant-in-Aid for Transformative Research Areas (A) 2022-2027

Revolution ofChiral Materials Science using Helical Light Fields

NEWS LETTER VOL 1

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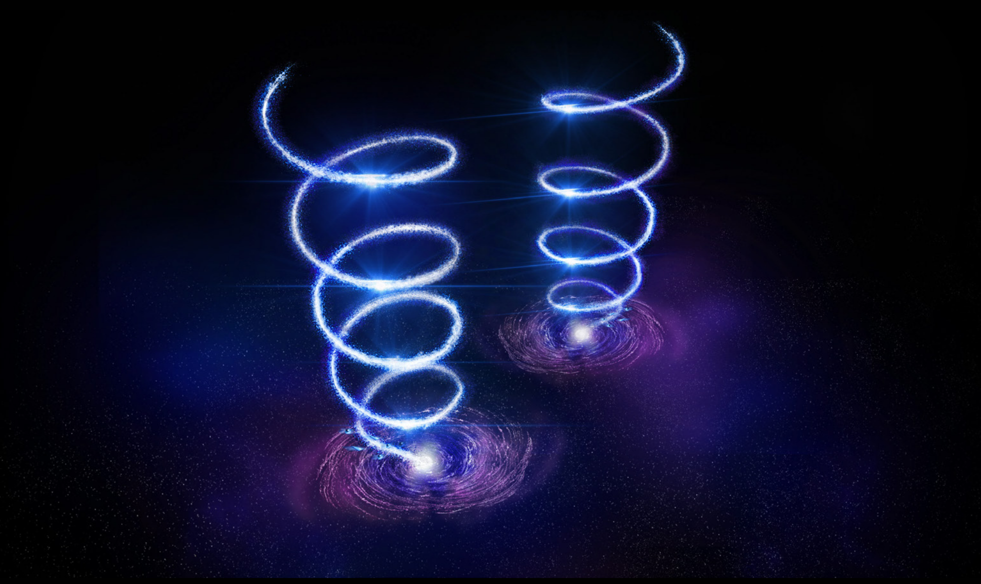
CONTENTS



Greetings

Chirality refers to the property where an object or phenomenon cannot be superimposed on its mirror image. Helicity of light is the helical electric field of circularly polarized light. The sub-micrometer-scale (corresponding to the wavelength of light) of the helical electric field is about two orders of magnitude larger than the nanometer-scale of the molecules, thus resulting in almost no interaction between circular polarization and the chirality of the matter. In fact, up to now, circular polarization has been widely used to detect the chirality of matter, but with a few exceptions, the difference in light absorption between left and right circular polarizations, referred circular dichroism, is only less than 1/100th of the total absorption strength of the molecule. Therefore, it has traditionally been considered extremely difficult to organize matter in chiral structures by the helicity of light.

However, recent innovative advances in laser and microfabrication technologies are now significantly evolving the light-matter interaction based on helicity of light beyond the circular dichroism. In 1992, Allen suggested the importance of light with a helical wavefront, namely, optical vortices. The wavefront helicity (the number of twists per wavelength) is defined by the order ℓ (±1, ±2, ±3, ...), and in principle, ℓ can take infinitely large values. Also, the development of nano and microfabrication has led to the advancement of nanophotonics and plasmonics. When light is incident on a plasmonic metal nanostructure, near-field is localized on the surface of the nanostructure. Its effective wavelength is much smaller than that of the incident light, thus enhancing significantly the electric field and helicity (number of rotations per wavelength of the electric field) of the incident light.
Going beyond conventional circularly polarized light fields, optical vortices and helical near-fields are here referred 'helical light fields'.

The strong helicity of such helical light fields may be possible to hierarchically assemble and order versatile materials to establish chiral structures. In fact, recent discoveries show that helical light fields hierarchically assemble chiral structures of materials such as molecules, polymers, and resins at high efficiencies.

However, the helical light field induced chiral structuring of materials cannot be completely explained by conventional light-matter interaction theories based on optical radiation pressure. To fully understand how and why a helical light field enables the formation of chiral structures, systematic studies to deeply explore the fundamentals of the helical light and matter interactions is needed.

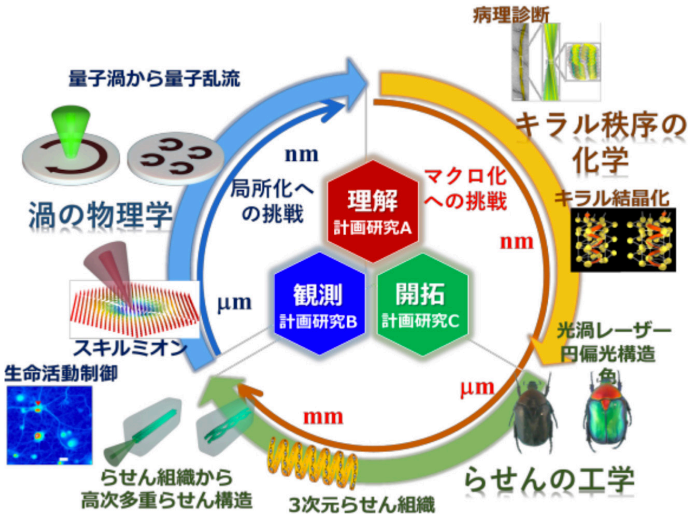
The goal of this Transformative Research Area is the ultimate dream of material scientists:

Greetings

'to fabricate chiral structures of versatile materials with different spatial scales with light', and ‘to bring about a revolution in materials science’. Furthermore, it is to create new scientific revolutions and innovative technologies by utilizing the potential of helical light fields from a cross-disciplinary study beyond conventional physics, chemistry, and life sciences. We hope that many people will join us in exploring the cross-cutting sciences and technologies based on helical light fields.

Appplied/Development Research

This research project provides a ripple effect with a wide range of areas. We herein aim three applied developments based on the chiral structuring of materials, <Chemistry of Chiral Order>, <Engineering of Spirals>, and <Physics of Vortices>.



Chemistry of Chiral Order

Achievement of chiral crystallization with a near 100% enantiomeric excess rate by using helical light fields will pave the way towards the possibility of homochirality in nature via helicity of light. Elucidation of the chiral crystallization mechanism will enable the ultra-sensitive detection of chiral substances and the development of pathological markers, and it will furthermore contribute to synthetic chemistry, drug discovery, and biomedical engineering.

Engineering of Spirals

Chiral structures of molecular aggregates using helical light fields will realize advanced devices, such as circularly polarized structural colors and circularly polarized/optical vortex emitting lasers. Also, the artificially designed chiral structures of biological tissues or biocompatible materials will exhibit exotic physical and chemical properties not found in nature.

Physics of Vortices

Direct imprint of the helicity of helical light field to matter will explore new fundamental physics, such as the creation and annihilation of skyrmions and the manipulation of quantized vortices to understand the unresolved problem of turbulence in physics.

These aforementioned applied developments in this research project are challenges toward our ultimate dream, and they aim to realize strongly linkage among planned research projects.

Research Project A Introduction

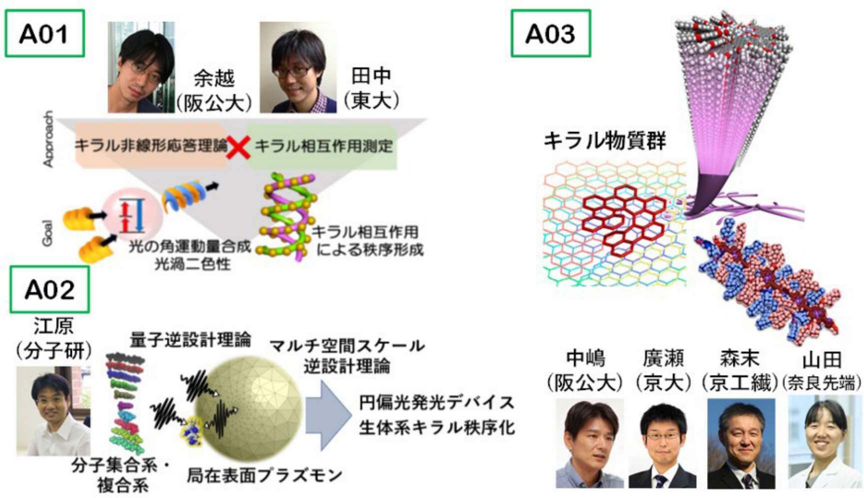
Takuya Nakashima, Graduate School of Science, Osaka Metropolitan University

Group A focuses on the elementary processes of 'Chiral Ordering' induced by helical light field, aiming to deepen theoretical understanding and provide guidelines for exploring innovative materials for novel chiral ordering. The group is composed of three research projects. Each planned research is led by Yokoshi (A01), who researches the physical theory of interactions between spatially designed light fields such as localized surface plasmons and optical vortices with matter; Ehara (A02), who has been working on the development and application of the quantum state theory of excited states of molecules and molecular aggregates; and Nakashima (A03), who has achievements in controlling the chiral structure of molecules and molecular aggregates and developing chiroptical properties such as circularly polarized light luminescence.

Planned research A01 aims to develop a theory of 'Nonlinear chiral optical responses by helical light fields' and to understand the conversion of orbital angular momentum and chirality from light to materials at the single photon level, challenging a new development of 'Chiral Ordering.' In addition, by collaborating with Tanaka (co-researcher) on experiments related to the helicity of light and interactions with chiral molecules, we will explore the possibility of high-sensitivity spectroscopy of chiral molecules.

Planned research A02 promotes the construction of a 'Quantum Inverse Design Theory of Chiral Optical Properties Based on Helical Light Field,' aiming at the design of molecules and aggregates that realize extreme chiral optical properties. It focuses on metal nanoparticle-molecule systems to develop a quantum inverse design theory capable of designing molecular systems and photon fields that achieve desired chiral optical properties.

Planned research A03 aims for 'Coherent Control of Excitons in Chiral Molecular Systems through Interaction between Helical Light Field,' developing molecules and aggregates with chiral order that concertedly control helical light field and exciton behavior. Furthermore, in collaboration with Hirose, Morisue, and Yamada (co-researchers), it supports inter-domain joint research in material aspects using a wide range of chiral molecular materials such as photoresponsive molecules, helicene molecules, and near-infrared light active molecules.



Through these planned studies, the group aims to establish the theoretical basis for the elementary processes of Chiral Ordering, such as the exchange of angular momentum between light and matter, and the spin-orbit interaction of light.

Research Project B Introduction

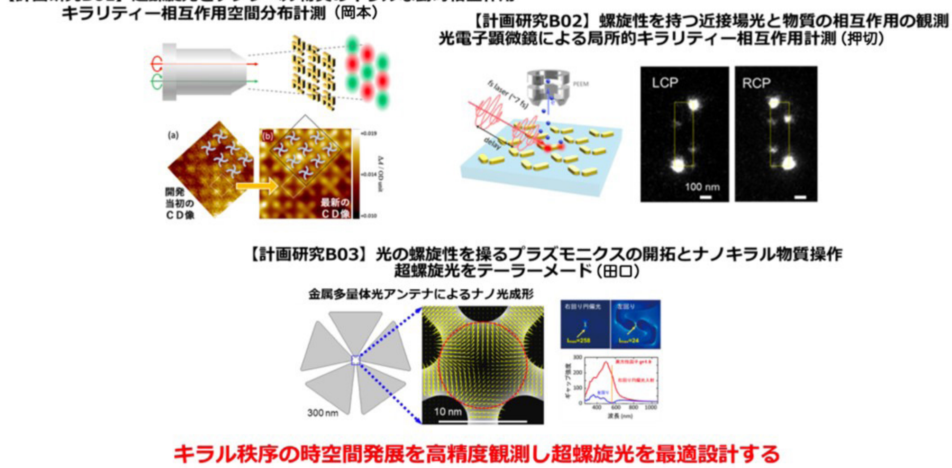
Hiromi Okamoto, Center for Mesoscopic Sciences, Institute for Molecular Science

Group B pioneers and develops unique methods for observing the helicity and chiral order of materials. The Group is responsible for characterizing the various chiral orders created by helical light field in this Transformative Research Area, and for analyzing their formation mechanisms. The project also includes research on creating fields that generate helical light field using nanofabrication techniques.

In planned research B01, Okamoto, from a viewpoint of physical chemistry, has promoted researches to elucidate and control the unique optical properties of nanomaterials using experimental methods of nanooptical imaging. Recently, he developed a circular dichroism microscopy based on a unique technology, and has been conducting characterizations of chiral materials through collaborative researches. In this Transformative Research Area, this method will be used as a basis for evaluating chiral order creation by helical light fields, and based on the knowledge obtained, attempts will be made to create new chiral orders and pursue the fundamental principles of light-matter interaction that drives them.

In planned research B02, Oshikiri has focused on near-field control by localized plasmons and their application to chemical reactions. He has also developed methods for observing localized optical fields in nanospaces through near-field imaging using multiphoton photoemission electron microscopes. In the present project, he will clarify how the helicity of the incident light is transcribed into the optical near-field near nanostructures under circularly polarized light irradiation, and how the transcribed helicity affects molecules. He will also explore chiral ordering on a macroscopic spatial scale.

In planned research B03, Taguchi has promoted researches in the field of nanophotonics, especially the interaction between metal nanostructures and light in the deep ultraviolet range. In the present project, he will promote the development of theories related to the generation and application of nano-optical fields that include spin and orbital angular momentum, by metal nanostructures. He will design and fabricate metal nanostructures that realize nano-optical vortex fields with dramatically increased localization and enhancement, from the ultraviolet to visible light range, and explore chiral interaction phenomena with molecules and two-dimensional nanomaterials.

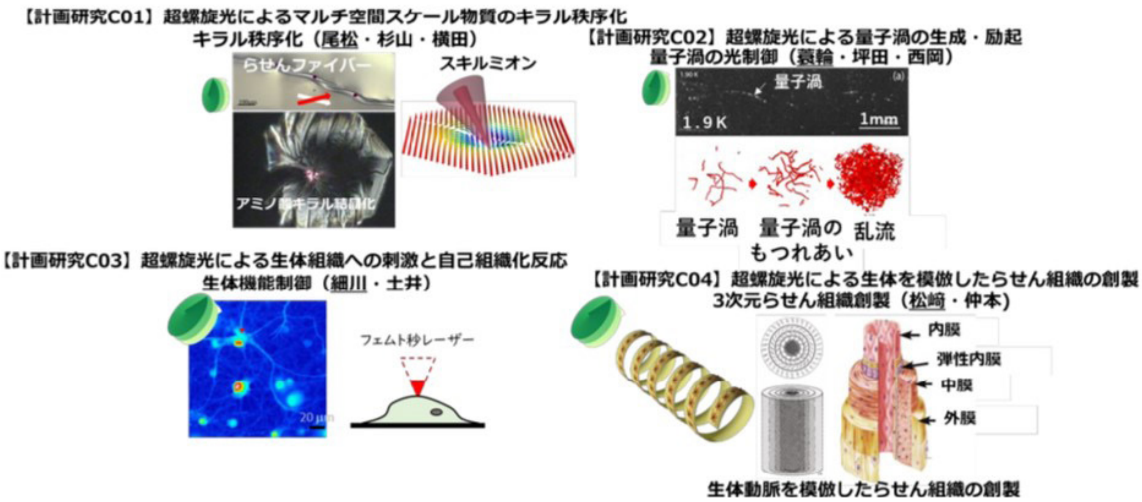


Research Project C Introduction

Takashi Omatsu, Graduate School of Engineering, Chiba University

Group C is composed of four planned research projects led by Omatsu, a pioneer in chiral structures fabrication with helical light fields; Minowa, who visualizes quantized vortices in superfluid helium; Hosokawa, who manipulates living cells dynamics through light pressure; and Matsusaki, an expert in construction of biomimetic 3-dimensional structures with cellular function expression and intercellular adhesion control. The group aims to explore novel chiral structuring induced by interaction between helical light fields and materials. For instance, ultimate chiral crystallization, optical creation and annihilation of skyrmions, the generation and control of quantized vortices, manipulation of biological materials to realize new cellular function manipulations, creation of 3-dimensional spiral structures mimicking biological tissues etc.

The group further aims to apply these developments to transplant tissues engineering and drug discovery technologies.



Team Composition & Aspirations

A01 Nonlinear chiral optical responses by helical light fields

Principal Investigator	Nobuhiko Yokoshi, Osaka Metropolitan University, Graduate School of Engineering
Co-Researcher	Yoshito Tanaka, University of Tokyo

We review angular momentum exchanges between helical light fields and matters from a physical perspective, and develop new functionalities through measurements of chiral light-matter interactions.

A02 Quantum inverse design theory for the chiroptical properties based on helical light fields

Principal Investigator	Masahiro Ehara, National Institutes for Natural Sciences

We aim to understand the interaction between helical light field and matter and to conduct the researches on chiral optical properties and functions using quantum inverse design theory.

A03 Coherent control of excitons in chiral molecular systems through interactions with helical light fields

Principal Investigator	Takuya Nakashima, Osaka Metropolitan University, Graduate School of Science
Co-Researcher	Takashi Hirose, Kyoto University Mitsuhiko Morisue, Kyoto Institute of Technology Miho Yamada, Nara Institute of Science and Technology

As a unique team in material synthesis, we advance the development of molecules and nanomaterials that interact with helical light field to demonstrate innovative properties.

B01 Chiral interaction dynamics between helical light fields and nanomaterials

Principal Investigator	Hiromi Okamoto, Institute for Molecular Science
Co-Researcher	Mark Sadgrove, Tokyo University of Science, Department of Physics Tetsuya Narushima, Institute for Molecular Science Hyo-Yong Ahn, National Institute of Natural Science Junsuke Yamanishi, Institute for Molecular Science

We would like to contribute to the construction of scientific principles on creation of helical light fields and chiral orders using unique technologies like circular dichroism microscopic imaging.

Team Composition & Aspirations

B02 Interaction between material and helical near field

Principal Investigator	Tomoya Oshikiri, Tohoku University, Institute of Multidisciplinary Research for Advanced Materials
Co-Researcher	Takehiko Wada, Tohoku University, Institute of Multidisciplinary Research for Advanced Materials

We aim to develop the observation method of interactions between helical light field and materials near nanostructures, and understand the principle of the light-matter interaction in helical near-field.

B03 Nanoscale Helical Field Generations and Material Manipulations using Plasmonics

Principal Investigator	Atsushi Taguchi, Institute of Electronics Science, Hokkaido University

We explore plasmonics to manipulate helically structured light fields at the nanoscale, pioneering nano-science of chiral-light-matter interactions.

C01 Nano/macro-scale chiral structures fabricated by illumination of helical light fields

Principal Investigator	Takashige Omatsu, Chiba University, Graduate School of Engineering
Co-Researcher	Hiroko Yokota, Chiba University, Graduate School of Science Teruki Sugiyama, Nara Institute of Science and Technology, Graduate School of Materials Science

We explore chiral structures using helical light field based on advanced laser technologies, and we also create new fundamentals and innovative light technologies based on interaction between helical light field and materials.

C02 Excitation of quantized vortex via helical light field

Principal Investigator	Yosuke Minowa, Osaka University, Graduate School of Engineering Science
Co-Researcher	Makoto Tsubota, Osaka Metropolitan University, Graduate School of Science Takashi Nishioka, Kochi University, Faculty of Science and Technology, Department of Mathematics and Physics

We aim to reveal chiral ordering process and principles by light using the unique characteristics of extremely low temperature, superfluidity, and nanoparticles.

Team Composition & Aspirations

C03 Stimulation into Biological Tissues and Self-Organization Dynamics using Helical Light Fields

Principal Investigator	Chie Hosokawa, Osaka Metropolitan University, Graduate School of Science
Co-Researcher	Kentaro Doi, Toyohashi University of Technology, Graduate School of Engineering

We aim to achieve spatiotemporal manipulation of biomolecules and cells using the external forces induced by the helical light field and explore its theoretical underpinnings.

C04 Development of 3D-tissues with helical structures by helical light field

Principal Investigator	Noriya Matsusaki, Osaka University, Graduate School of Engineering
Co-Researcher	Masahiko Nakamoto, Osaka University, Graduate School of Engineering Kenta Honma, Osaka University, Graduate School of Engineering

In this research, we aim to elucidate the theory of spiral structures in biological tissues by merging helical light field with tissue engineering and seek practical applications in the medical field.

Field Evaluation Committee & Advisors

To promote timely and smoothly this research project, we appoint 'Advisors,' who provide comments and advice based on their advanced expertise and experience, and 'Reviewers,' who evaluate this research project from a broad perspective.

Reviewers	Eiji Yashima, Nagoya University Toyohiko Yatagai, Utsunomiya University Hiroshi Masuhara, National Yang Ming Chiao Tung University Tohru Suemoto, University of Electro-Communications
Advisors	Kazue Kurihara, Tohoku University Yoshie Harada, Osaka University Keiji Sasaki, Hokkaido University Yasushi Inouye, Osaka University
International Advisors	Kishan Dholakia, University of Adelaide and University of St Andrews Halina Rubinsztein-Dunlop, The University of Queensland Malcolm Kadodwala, University of Glasgow Alexander Govorov, Ohio University

Field Kick-off Symposium

On Thursday, September 1, 2022, from 1:00 PM, the research project Kick-off Symposium was held in a hybrid format, both at the Chiba University Conference Room (on-site) and online. There were about 200 participants combined from on-site and online. We sincerely thank everyone for their participation.

In the symposium, Professor Takashi Omatsu, the head investigator, explained the purpose and dreams behind the establishment of this research project. Also, Professor Hiroshi Masuhara from National Yang Ming Chiao Tung University (Taiwan) gave a lecture on his current research findings under the title 'Nonlinearly Evolved Dynamics of Optical Trapping and Photoexcitation of Nanoparticles at Interface', and expressed his expectations and support for this project. This was followed by presentations from planned research representatives, and expectations for Publicly Offered Researches from the head investigator. During the final Q&A session, there were many questions from the audience about the objectives of the research project, future prospects, and publicly offered research.

Press Releases, Awards, etc.

- Takashige Omatsu (Chiba University), the head investigator and head of planning team C01, received the 2022 Taizan Award (Laser Advancement Prize).
- A paper by Hiromi Okamoto (Institute of Molecular Science) of planning team B01 was published in Science Advances and a press release was issued. https://www.ims.ac.jp/news/2022/09/0922.html
- A paper by Takuya Nakashima (Osaka Public University) of planning team A03 was published in the Chemistry of Materials journal. https://doi.org/10.1021/acs.chemmater.2c01994

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Chair : Takashige Omatsu, Chiba University