【Grant-in-Aid for Transformative Research Areas（B）】

Ladder Polymer Science: Innovation through Ladder Bonding

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Project Information	Project Number : 25B206　Project Period (FY) : 2025-2027 Keywords : Higher-order structure, Reaction design, Polymer property, Nanospace, Silicon chemistry

Purpose and Background of the Research

●Outline of the Research

Since Staudinger proposed the “macromolecular hypothesis” in 1920, polymer science has continued to develop over the past 100 years as a crucial field of research, deeply involved in a wide range of fields, from cutting-edge materials science to life sciences. Polymers are generally recognized as giant molecules composed of small units called “monomers” that are covalently linked together in a single chain-like fashion, and can be imagined as a beads necklace at the molecular level.

Then, what would happen if we added another bond between the monomer units?

Such polymers are called ladder polymers. In conventional (single-stranded) polymers, only a single bond connects the monomer units, allowing free rotation around the bond axis. As a result, the overall macromolecular structure tends to be disordered. In contrast, in ladder polymers, two or more chemical bonds connect between adjacent monomer units, severely constraining the conformation along the main chain. Hence, the structural order is dramatically increased. This "addition of just one more chemical bond" restricts conformational freedom, potentially leading to critical differences between single-stranded polymers and ladder polymers.

This simple design concept of adding a second bond to polymers has the potential to advance polymer science from both a structural and functional perspective. However, the synthesis of ladder polymers remains challenging. This research project aims to achieve: (1) innovation in the synthesis of ladder polymers, (2) dramatic expansion of the structural diversity, and (3) elucidation of physical properties and development of advanced functionalities, pioneering the future of "ladder polymer science”.

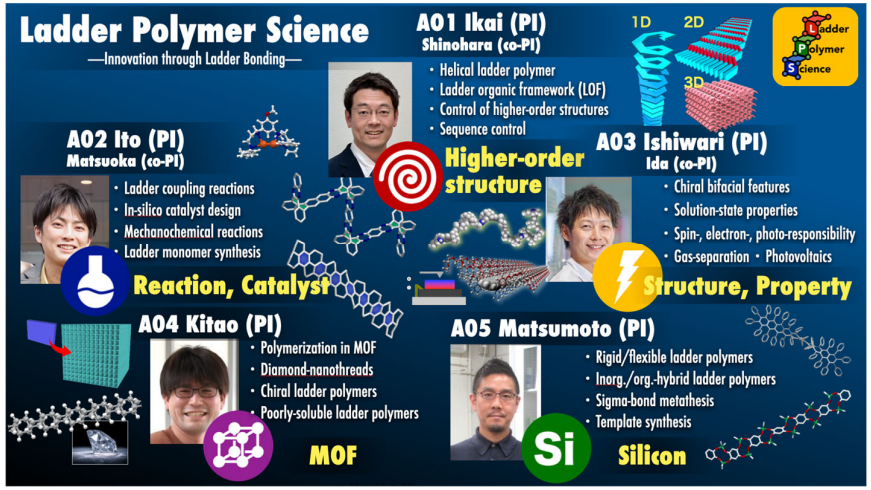

Figure 1. Schematic overview of our research project.

Expected Research Achievements

●Project Goals

This project aims to establish a new academic field of “Ladder Polymer Science.” It will lead the next generation of materials science through multidimensional and comprehensive studies, ranging from technological innovations in the precise synthesis of ladder polymers to the exploration of their physical properties and the development of advanced functionalities. Driven by the fundamental curiosity of scientists to create what does not yet exist, to take on difficult challenges, and to reveal the properties and functions of unexplored substances, this project promotes a novel materials design concept centered on the formation of ladder structures. We believe that this approach will not only open new avenues in polymer science, organic chemistry, and materials science, but also foster the emergence of innovative interdisciplinary fields across inorganic chemistry, biochemistry, physics, surface science, and electrical engineering.

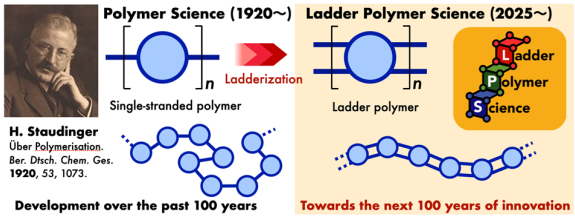

Figure 2. Conventional polymer science (left) and ladder polymer science (right).

●Project Organization and Challenges

A01 : Tomoyuki Ikai (PI Nagoya Univ.) ・ Ken-ichi Shinohara (co-PI JAIST)
「Science of Ladder Polymer-Based Organic Frameworks」

A02 : Hideto Ito (PI Nagoya Univ.) ・ Wataru Matsuoka (co-PI Hokkaido Univ.)
「Synthetic Ladder Polymer Chemistry Pioneered by Novel Methodologies」

A03 : Fumitaka Ishiwari (PI Tokyo Metropolitan Univ.) ・ Daichi Ida (co-PI Kyoto Univ.)
「Synthesis and Function of Ladder Polymers with New Structural Features」

A04 : Takashi Kitao (PI AIST)
「Precision Synthesis of Ladder Polymers Enabled by Porous Metal Complexes」

A05 : Kazuhiro Matsumoto (PI AIST)
「Silicon–Oxygen Bond-Directed Construction of Ladder Polymers」

●Project Implementation Plan

The five project groups each set different types of ladder polymers with distinct characteristics as their synthesis targets, focusing specifically on “ladder polymers with higher-order structures,” “fully conjugated ladder polymers,” “ladder polymers of designed architectures,” “diamond nanothreads,” and “flexible ladder polymers containing multiple siloxane bonds.” Initially, each group aims to establish precise synthesis methodologies for these targets.

The PIs of each group are experts in secondary structure control (A01), reaction design and synthesis (A02), molecular structure analysis (A03), nanoscale applications (A04), and silicon chemistry and asymmetric synthesis (A05), respectively. All group members collaborate closely to promote seamless precise synthesis, structural control, property investigation, and functional exploration. In addition, in collaboration with three co-investigators, the project will advance the in silico design of catalysts for ladder polymer synthesis, the physical property analysis of the resulting ladder polymers, and the elucidation of their dynamic behavior by molecular dynamics simulations to uncover novel physical properties and application potentials distinct from those of conventional single-stranded polymers.

Homepage Address, etc.	http://ladder-polymer-science.jp