

FUSION: Stimuli-Responsive Polymer-Stabilized Ferronematics for Ultrafast Actuation and Sensing

Liquid crystals might sound like a contradiction - how can any material be both a liquid and a crystal at the same time? Yet these remarkable soft materials combine features of both states. They flow like ordinary liquids but still preserve a certain degree of internal order by lining up their molecules in a specific direction. The simplest type of liquid crystal, the nematic phase, is made of long, rod-like molecules that point in roughly the same direction yet do not have a fixed position like in a solid crystal. Since their discovery in 1888 by Friedrich Reinitzer and Otto Lehmann, scientists have found many different liquid crystal phases, each with unique structures and uses. Their most widespread application is in the screens of TVs, computers, and smartphones.

In this project, we explore a newly discovered type of liquid crystal known as ferroelectric nematics (N_F). Ferroelectric materials naturally develop an internal electric field because their molecules or pairs of ions in their crystalline lattice arrange their dipoles parallel to each other, i.e., in a polar manner. Amazingly, over a hundred years ago, physicists Max Born and Peter Debye predicted that such electric ordering could also exist in liquid crystals. However, it was not proved until 2017 when researchers in Japan and the UK synthesized molecules that showed this "ferro(electric)nematic" behavior. More recently, in 2024, scientists at the University of Warsaw and the Military University of Technology identified a twist-bend ferronematic (N_{TB}) phase, which arranges its electric dipoles in a screw-like (helical) pattern. The N_F phases possess multiple unusual properties. One particularly notable feature of their polar nature is their exceptionally high responsiveness to electric fields - these materials react hundreds of times more strongly than conventional nematics. Even more intriguingly, without any applied fields, they can spontaneously produce thin, liquid filaments that resemble Spider-Man's spider silk. Thanks to dipolar stabilization, even very long filaments defy surface tension and remain surprisingly stable. In addition, molecules in fibers in the N_{TB} phase adopt a helical structure that can bend and reflect light, with their optical behavior depending on both temperature and electric fields. The properties of N_F phases open the door to ultrafast responsive electrooptical devices, e.g., switchable color and polarization filters, light steering, or detection of environmental changes. We are confident that N_F materials will continue to yield surprising developments in the years ahead.

However, despite this incredible potential, ferroelectric nematic liquid crystals have some practical issues. They are soft, easily deformable, and do not last as long as we would like without support. Our solution to reinforce them is by wrapping them with flexible yet durable cushions - specially designed polymer membranes. This approach should give them the mechanical strength and durability they need while preserving their extraordinary responsiveness. In this project, our main goals are to 1) test ferroelectric nematics as adaptable optical and electrical sensors and actuators, 2) figure out how quickly and effectively these super-thin materials can respond to various external cues, 3) explore how their mechanical behavior changes with temperature when confined to thin membranes, 4) improve their performance to make it easy to include them in practical devices.

Tackling these challenges will help us push the limits of what "soft matter" can do, uncovering new relationships between the materials' architecture and properties and breaking through current barriers in stability and strength. The polymer coatings we are working with are incredibly stable and can form membranes that are tens of thousands of times thinner than their width yet can withstand temperatures up to 400°C. Combining these coatings with ferroelectric nematics could create rapid-response materials, e.g., ultrathin membranes or fibers that react within milliseconds to changes in electric field, laser light, temperature, or even humidity. Such breakthroughs can lead to next-generation sensors, miniaturized actuators for the propulsion of microrobots, and other advanced technologies that bring the exceptional properties of ferroelectric liquid crystals into everyday applications.