Introduction to the Special Issue on Singular Optics
Modern Trends and Prospects of Singular Optics

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This special issue on Singular Optics brings together cutting-edge research reflecting the field's current state and key development trends. Over the past few decades, the discipline has evolved from the study of isolated optical defects – such as phase and polarization singularities emerging in the transverse fields of paraxial light beams – into a much broader concept encompassing the generation, control, and characterization of the topology and spatiotemporal structure of light fields, as well as the targeted manipulation of their interaction with matter.

Modern singular optics embraces complex structured optical fields characterized by complicated 3D singular textures, such as optical skyrmions, merons, hopfions, optical knots and links, Möbius structures, and other topologically nontrivial configurations. The involvement of temporal dimensions and non-simply connected wave-carrier spatial regions naturally introduces spatio-temporal singularities and high-intensity singularities (type-II optical vortices) into scientific discourse. In this context, a distinctive "topological language of light" is developing, wherein intricate spatial, polarization, and spatiotemporal structures can be constructed, combined, and transformed, using the interrelated networks of fundamental singular elements – singular skeletons. This evolution can be conceptualized as a transition from classical singular optics – via the paradigm of structured light – to the realm of topologically controlled optical fields, where singularities are no longer merely objects of study but serve as functional elements within complex topological structures.

One of the most promising directions in development is spatio-temporal singular optics, where, in addition to traditional spatial coordinates, time acts as a full-fledged degree of freedom of the optical field. This feature is spectacularly realized in space-time optical vortices (STOV), where the singularity appears in the spatio-temporal plane, and the orbital angular momentum is oriented perpendicularly to the propagation direction. The combination of spatial, temporal, and topological structurization of light opens up fundamentally new possibilities for controlling ultrashort light pulses, investigating attosecond electron dynamics, generating and manipulating complex harmonic spectra, and establishing new regimes of light-matter interaction. Spatio-temporal wave packets and STOVs are of particular interest, as coupling between spatial and spectral degrees of freedom enables the formation of light fields with prescribed topological properties.

A key area of modern research involves propagating singular and structured light fields in complex optical media—such as media with a spatially inhomogeneous refractive index, strongly scattering and/or absorbing media, biological tissues, and stochastic media characterized by natural (atmospheric) or laboratory turbulence. Such media interact with topologically structured light, transforming the field's phase, amplitude, polarization, and spatiotemporal characteristics. Crucially, these transformations can encode information about the medium's properties, providing a basis for solving inverse problems: reconstructing the medium's optical parameters from observed changes in the light field structure. In corresponding retrieval procedures, singularities may serve as highly sensitive markers of local variations in an object's or medium's properties, while their topological invariants (e.g., topological charge, skyrmionic number, etc.) provide robust markers of global field organization.

This approach establishes a promising direction in topological metrology and diagnostics, where the topological properties of light are utilized not only for information transmission but also as a measurement tool. Potential applications include micro- and nanoscale metrology, characterization of surfaces and thin structures, monitoring of material properties, diagnostics of inhomogeneous media, biomedical research, and imaging with enhanced spatial, phase, or functional resolution. Of particular promise is using robust or predictably transformable topological characteristics as information carriers, which may be less sensitive to local field distortions than traditional optical-field parameters.

Another important development involves the interaction of single light fields with metasurfaces, nanoparticles, dielectric nanostructures, plasmonic systems, and photonic resonators. In such situations, both the light field and the medium it interacts with are structured. This approach enables the simultaneous control of light topology and the material's spatio-spectral properties, potentially leading to novel light-matter interaction regimes, the manipulation of optical forces and torques, and the creation of high-quality-factor sensors, nonlinear photonic systems, and miniaturized photonic devices. Ultimately, this marks a shift from structuring light to interactive topological co-design of light and matter.

Topological degrees of freedom of light are also especially important for the development of quantum optics. Orbital angular momentum and other spatial and spatiotemporal degrees of freedom in a photon create opportunities to generate high-dimensional quantum states and to encode and transmit information within high-dimensional state spaces. In this perspective, singular optics is increasingly interacting with quantum optics, quantum communications, quantum networks, and high-dimensional information transmission. Topologically structured fields can enable new principles for information encoding, routing, and processing by using not only intensity or polarization but a much broader set of controllable degrees of freedom.

Thus, singular optics is no longer merely a specialized field concerned with points or lines where the light-field phase is undetermined. It is gradually evolving into a universal framework for generating, describing, transforming, characterizing, and practically applying topologically complex light fields. Its modern development is driven less by the discovery of new types of singularities than by the ability to manipulate interactions among various degrees of freedom of light – spatial, temporal, spectral, polarization, and topological – and to use them as functional resources.

In this context, the future of singular optics likely lies in shifting from observing and classifying singularities to programmatically controlling light topology. A key challenge lies not only in creating new topological structures but also in developing methods to form, stabilize, modify, and read them out in real space and time. Controlled topology may serve as a novel tool for high-precision measurements, visualization, diagnostics of complex media, data transmission and processing, and the control of light-matter interactions. Viewed in this light, singular optics is gradually evolving from the optics of defects into the topological engineering of light.

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