POLARIZATION SINGULARITIES: SYNTHESIS, CHARACTERIZATION AND APPLICATION

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Polarization Singularities: Synthesis, Characterization and Application

by

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Dedicated to my family

Certificate

This is to certify that the thesis entitled **"Polarization Singularities: Synthesis, Characterization and Application"**, submitted by **Kapil Kumar Gangwar** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in Department of Physics, is a record of the original, bona fide research work carried out by him under our supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of our knowledge.

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Abstract

This thesis explores the generation, manipulation, and characterization of polarization singularities in structured light fields using innovative optical techniques. Polarization singularities, such as C-points and V-points, are topological features of vector beams that hold immense potential in singular optics. The work presented here is centered on developing efficient, controllable methods for creating singular beams, analyzing their properties, and studying their behavior under various conditions.

Novel strategies, including the use of Dammann gratings and phase ramps via spatial light modulators, are implemented to generate polarization singularity lattices with tunable indices and handedness. Composite polarization vortices are realized using a common-path polarization interferometer. This composite vortex is surrounded by C-point rings, and their properties are investigated through Stokes field analysis. Furthermore, a robust interference-based approach is proposed to identify and resolve degeneracy in the index. By finding spin and orbital angular momentum components, the degeneracy is lifted. The analysis of interference fringes with a tilted reference beam enables direct determination of the Stokes indices.

Furthermore, the effect of optical aberrations—specifically astigmatism—is investigated both theoretically and experimentally. By analyzing the transformation of intensity profiles under varying astigmatic strengths, the study demonstrates a quantifiable relationship between the aberration and the singularity structure. This provides a new method for characterizing both polarization singularities and lens aberrations, with implications in optical metrology and adaptive optics.

Theoretical predictions are consistently validated through detailed simulations and precise experiments, highlighting the practicality and accuracy of the proposed techniques. The findings have important implications for optical metrology, beam diagnostics, adaptive optics, and applications in optical trapping and free-space communication systems.

सार

यह शोध संरचित प्रकाश क्षेत्रों में ध्रुवण विषमताओं की उत्पत्ति, नियंत्रण और विशेषता निर्धारण की खोज करता है, जिसमें नवीन प्रकाशीय तकनीकों का उपयोग किया गया है। ध्रुवण विषमताएँ, जैसे कि सी–बिंदु और वी–बिंदु, सदिश प्रकाश किरणों की रूपात्मक विशेषताएँ होती हैं, जिनका विषम प्रकाशिकी में अत्यधिक महत्व है। इस कार्य में मुख्य रूप से प्रभावशाली और नियंत्रित विधियाँ विकसित की गई हैं, जिनके माध्यम से विशेष प्रकाश किरणों का निर्माण, उनके गुणों का विश्लेषण और विभिन्न परिस्थितियों में उनके व्यवहार का अध्ययन किया गया है।

डैमान जालियों और स्थानिक प्रकाश अधिमिश्रक के माध्यम से चरणीय वृद्धि जैसी नवीन रणनीतियों को अपनाते हुए, नियंत्रित सूचकांक और घूमाव दिशा वाले ध्रुवण विषमता जालों को बनाए गए हैं। एक सामान्य पथ पर आधारित ध्रुवण व्यतिकरण यंत्र का उपयोग कर मिश्रित ध्रुवण भंवर बनाए गए हैं, जो सी–बिंदुओं के वलयों से घिरे होते हैं। इनकी विशेषताओं का अध्ययन स्टोक्स क्षेत्रीय विश्लेषण द्वारा किया गया है। साथ ही, एक सशक्त व्यतिकरण आधारित विधि प्रस्तुत की गई है, जिसके माध्यम से सूचकांक की समानता की पहचान कर उसे हल किया गया है। इसमें घूर्णी संवेग के दोनों भागों — आंतरिक घूर्णन और कक्षीय घूर्णन — का निर्धारण कर विषमता को स्पष्ट किया गया है। एक झुके हुए संदर्भ प्रकाश की सहायता से बने व्यतिकरण धारियों का विश्लेषण करके स्टोक्स सूचकांकों का प्रत्यक्ष निर्धारण किया गया है।

प्रकाशीय दोषों, विशेष रूप से द्विअक्षीयता (ऐस्टिग्मैटिज़्म), का प्रभाव सैद्धांतिक और प्रयोगात्मक दोनों दृष्टिकोणों से जांचा गया है। विभिन्न स्तरों की द्विअक्षीयता के प्रभाव से उत्पन्न तीव्रता वितरण के परिवर्तन का अध्ययन कर यह दिखाया गया है कि दोष और ध्रुवण संरचना के बीच एक गणनीय संबंध होता है।

यह विधि ध्रुवण विषमताओं तथा लेंस दोषों के लक्षण निर्धारण की एक नई दिशा प्रस्तुत करती है, जिसका उपयोग प्रकाशीय मापन तथा अनुकूली प्रकाशिकी में किया जा सकता है। सैद्धांतिक पूर्वानुमानों को सटीक संख्यात्मक अनुकरणों तथा नियंत्रित प्रयोगों के माध्यम से सत्यापित किया गया है, जिससे प्रस्तुत विधियों की वास्तविक उपयोगिता और सटीकता स्पष्ट होती है। यह शोध परिणाम प्रकाशीय मापन, किरण परीक्षण, कण फँसाने की विधियों तथा मुक्त माध्यम संचार तंत्रों में महत्वपूर्ण योगदान प्रदान करते हैं।

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Abbreviations

PS	**P**oincaré **S**phere
HOPS	**H**igher **O**rder **P**oincaré **S**phere
HyOPS	**H**ybrid **O**rder **P**oincaré **S**phere
PH	**P**oincaré **H**opf
OAM	**O**rbital **A**ngular **M**omentum
SAM	**S**pin **A**ngular **M**omentum
SPP	**S**piral **P**hase **P**late
SLM	**S**patial **L**ight **M**odulator
SOP	**S**tate Of **P**olarization
RCP	**R**ight **C**ircularly **P**olarization
LCP	**L**eft **C**ircularly **P**olarization
HWP	**H**alf **W**ave **P**late
QWP	**Q**uarter **W**ave **P**late
PBS	**P**olarizing **B**eam **S**plitter
BS	**B**eam **S**plitter
SC	**S**tokes **C**amera
OV	**O**ptical **V**ortex
DG	**D**ammann **G**rating
CGHs	**C**omputer **G**enerated **H**olograms

Symbols

θ	azimuthal angle
θ_0	phase shift
ϕ	phase of optical field
r	radial coordinates
I_c	C-point index
η	Poincaré-Hopf index
λ	wavelength
$\hbar$	reduced Planck's constant
p, q	charge of optical vortex
E	electric field
γ	azimuth of polarization ellipses
χ	ellipticity of polarization ellipses
S_0, S_1, S_2, S_3	Stokes parameters