DESIGN AND EVALUATION OF STRUCTURED AND STRUCTURED-FREEFORM ELEMENTS FOR OPTICAL ENGINEERING

ASHISH DWIVEDI

DEPARTMENT OF PHYSICS

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

ASHISH DWIVEDI

Department of Physics

Submitted

in fulfilment of the requirements for the degree of Doctor of Philosophy

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Dedicated to,

My

Teachers,

Family,

&

Friends

Certificate

This is to certify that the thesis entitled "**DESIGN AND EVALUATION OF STRUCTURED AND STRUCTURED-FREEFORM ELEMENTS FOR OPTICAL ENGINEERING**" being submitted by **ASHISH DWIVEDI** to Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirements, which to our knowledge have reached the requisite standard for the submission of the thesis. The results contained in this thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

(Anurag Sharma)
Professor
Department of Physics
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110016, INDIA

(Gufran S. Khan)
Professor
Centre for Sensors, INstrumentation and
Cyber-physical Systems Engineering (SeNSE)
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110016, INDIA

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Abstract

The description, modeling, generation, and use of freeform surfaces in optical applications have enormous potential. It is already widely used in a number of applications in the field of illumination engineering, imaging, and solar concentrator optics. In this research work, a method known as point-by-point ray mapping for freeform surface generation for illumination is developed with the ability to redistribute collimated rays in a controlled manner at a target plane. The surface engineering method presented in this thesis can control the surface shape based on the input and target illumination pattern. The applicability of the surface description method is shown in the field of ophthalmology, display engineering, illumination, and metrology. The illumination and display problems solved in this thesis are suitable for various types of light sources, starting from natural light (ophthalmology) to LED and even laser source-based designs.

The goal of this research work is to design and evaluate structured and structured-freeform optics for illumination, intraocular lenses, and other micro optics based optical systems**.** The main objectives are;

- To identify the dependencies between parameters used to design freeform surface and corresponding performance associated with it
- To design and evaluate the optical surfaces generated by point by point ray mapping method for intraocular lenses
- To design and evaluate the structured, freeform, and structured-freeform optics for illumination applications using LED and laser sources.
- To design a simulation model of Shack Hartmann Sensor for approximation error estimation for freeform surfaces with steep slopes.

The first chapter outlines the background of freeform optics and its recent emergence over conventional optics. Then, applications of freeform elements in optical engineering, available manufacturing technologies are discussed. The challenges in defining freeform surface for manufacturing, metrology, and surface description, are also described. In the last part of the chapter, the freeform surface description and different design strategies are categorized. The application of imaging and illumination types is also reviewed.

The existing point-by-point ray mapping method for the design of freeform elements for illumination application is presented in chapter 2. Further, design strategies, mathematical formulations, and processes involved in the generation of various types of freeform surfaces are described. Finally, the discussed design strategies and structured and structured-freeform-based optical elements and their evaluation are presented in subsequent chapters.

In the third chapter, a potential solution for an ophthalmological anomaly, known as Negative Dysphotopsia occurs in a pseudophakic eye, is reported. Negative Dysphotopsia, which is a problem of shadow in the nasal side of the retinal region, is being illustrated using the schematic optical model of the human eye. The freeform surface generation method proposed in the second chapter is used to design a special edge profile of an ND-Ring. However, the element designed is still rotationally symmetric. It is further illustrated that the designed edge profile is capable of re-illuminating the shadow region; therefore, it is a potential solution for mitigating the Negative Dysphotopsia problem. In the last part of the chapter, the designed elements are evaluated in the optical model of the eye, and results are discussed.

The fourth chapter presents a concept of the structured-freeform optical element for laser spot illumination and its benefit over the conventional optical element used for this purpose. Further, its application in laser projection display, optical design, and evaluation with tolerancing are discussed in detail. In the last part of the chapter, an experimental evaluation of a prototype of a laser spot illuminator is also reported.

The fifth chapter describes the optical design of LED collimation lens using the point-by-point ray mapping method. Design and evaluation are discussed for different types of LED collimators. Further, structured rotationally symmetric and structured-freeform elements are designed and evaluated for illumination redistribution using the method described in the second chapter. As an example, rotationally symmetric structured elements for uniform and focused illumination are discussed. Also, two sets of structured-freeform elements are also designed for prescribed illumination application. These are also analyzed by the ray-tracing method at the end of the chapter.

The challenges and limitations due to approximation errors involved in the measurement of the steep freeform wavefront by using Shack-Hartmann Sensor (SHS) are addressed in the sixth chapter. Zemax simulation tool is used to design a SHS setup, and estimation of errors associated with approximation are taken in the SHS measurement method.

In the last chapter, major conclusions drawn from the thesis with notes on the future scope for further investigations are discussed as a conclusion.

सार

ऑप्टिकल अनुप्रयोगों में मुक्ताकार सतहों के विवरण, प्रतिरूपण, विनिर्माण और उपयोग में प्रबल संभावनाएं हैं। यह पहले से ही व्यापक रूप से प्रकाशिक अभियांत्रिकी , चित्रण और सौर सांद्रक प्रकाशिकी के क्षेत्र में उपयोग किया जाता है। इस शोध कार्य में, प्रकाश के लिए मुक्ताकार सतह विनिर्माण के लिए बिंदु-दर-बिंदु किरण मानचित्रण के रूप में जाना जाने वाला एक तरीका विकसित किया गया है, जिसमें लक्षित सतह पर नियंत्रित तरीके से कोलिमिटेड किरणों को पुनर्वितरित करने की क्षमता है। इस शोध प्रबंध में प्रस्तुत सतह अभियांत्रिकी तकनीक दिया गया और लक्ष्य प्रकाशिक पैटर्न के आधार पर सतह के आकार को नियंत्रित कर सकती है। सतह विवरण विधि की प्रयोज्यता नेत्र विज्ञान, प्रदर्शन अभियांत्रिकी, प्रकाश और परिमापन के क्षेत्र में दिखाई जाती है। इस शोध प्रबंध में हल की गई प्रकाश और प्रदर्शन की समस्याएं प्राकृतिक प्रकाश (नेत्र विज्ञान) से लेकर एलईडी और यहां तक कि लेजर स्रोत-आधारित प्रतिरूपण तक विभिन्न प्रकार के प्रकाश स्रोतों के लिए उपयुक्त हैं।

इस शोध कार्य का लक्ष्य प्रकाशिकी, अंतःकोशिकीय और अन्य माइक्रो ऑप्टिक्स आधारित ऑप्टिकल सिस्टम के लिए संरचित और संरचित- मुक्ताकार प्रकाशिकी का प्रतिरूपण और मूल्यांकन करना है। मुख्य उद्देश्य हैं;

- मुक्ताकार सतह को प्रतिरूपण करने के लिए उपयोग किए जाने वाले मापदंडों और इससे जुड़े प्रदर्शन के बीच निर्भरता की पहचान।
- अंतःकोशिकीय लेंसों के लिए बिंदु-दर-बिंदु किरण मानचित्रण विधि द्वारा उत्पन्न मुक्ताकार प्रकाशिक सतहों मूल्यांकन करना
- एलईडी और लेजर स्रोतों का उपयोग करके प्रकाशिकी के अनुप्रयोगों के लिए संरचित, मुक्ताकार और संरचित- मुक्ताकार प्रकाशिकी का प्रतिरूपण और मूल्यांकन करना।

खड़ी ढलानों के साथ मुक्ताकार सतहों के लिए सन्निकटन त्रुटि आकलन के लिए शेक हार्टमैन सेंसर के सिमुलेशन मॉडल का प्रतिरूपण करना।

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List of Abbreviation

CNC	Computer Numerical Control
PAL	Progressive Addition Lens, and
	Panoramic Annular Lens
HDM	Head Mounted Display
LED	Light Emitting Diode
(PPLs)	Progressive Power Lenses
CPC	Compound parabolic Concentrator
RR	Refractive and Reflective
SPDT	Single Point Diamond Turning
STS	Slow Tool Servo
FTS	Fast Tool Servo
MRF	Magnetorheological Finishing
DTM	Diamond Turning Machining
CMM	Coordinate Measuring Machine
CCD	Charge Couple Device
SHS	Shack-Hartmann Sensor
NAT	Nodal Aberration Theory
NURBS	Non-Uniform Rational B-Spline
SMS	Simultaneous Multiple Surface
PDE	Partial Differential Equations
SQM	Supporting Quadratic Method
DOE	Diffractive Optical Element
TIR	Total Internal Reflection
SPM	Slope Point Method
MTF	Modulation Transfer Function
RMS	Root Mean Square
SAM	Simple Approximation Method
IOL	Intraocular lenses
ND	Negative Dysphotopsia.

PD	Positive Dysphotopsia
CAD	Computer Aided Design
NU	No uniformity
CV	Corner variation
MLA	Micro Lens Array
TPWF	Tilted Plane Wavefront
TCWF	Tilted Curved Wavefront
PV	Peak to Valley