

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

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

by

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to the



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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.

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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 परिमाणन 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।

Contents

Certificate	i
Contents	viii
List of figures.....	xiii
List of tables.....	xix
1 Chapter 1: Introduction to freeform optics	1
1.1 Background	1
1.2 Applications of freeform Optics	4
1.3 Manufacturing technologies and limitations for freeforms.....	6
1.3.1 Ultra-precision Machining.....	6
1.3.2 Precision Milling.....	7
1.3.3 Ultraprecision deterministic polishing process.....	8
1.4 Freeform metrology techniques and limitations for freeform optics	10
1.5 Design challenges for freeform optical surface	11
1.5.1 Surface representation	11
1.5.2 3rd order Seidel Vs Nodal Aberration Theory.....	12
1.5.3 Tolerancing of freeform optical surface	12
1.6 Generalized optical surface representation techniques	13
1.6.1 Freeform surface description for imaging applications	14
1.6.1.1 XY polynomial.....	15
1.6.1.2 Φ -function (Radial polynomial).....	15
1.6.1.3 Zernike-polynomials	16
1.6.1.4 Modified Zernike polynomials.....	17
1.6.1.5 Q-type polynomials.....	18
1.6.1.6 Chebyshev polynomials	18
1.6.1.7 Legendre polynomial	19
1.6.1.8 A-polynomial of type I & II.....	19
1.7 Freeform surface description for imaging and illumination applications	20
1.7.1 Non-Uniform Rational B-Spline (NURBS)	22
1.7.2 Simultaneous Multiple Surface (SMS).....	22
1.7.3 Phase Space method	23
1.8 Freeform surface description for Illumination application.....	24
1.8.1 Solution of Partial Differential Equations	24
1.8.2 Supporting Quadratic Method (SQM).....	24

1.8.3	Point by Point Ray Mapping.....	24
1.9	Merit function optimization.....	25
1.10	Tolerancing of freeform surfaces.....	26
2	Chapter 2 Surface design methods for illumination engineering applications.....	29
2.1	Background.....	29
2.2	Design strategy by Point-by-point ray mapping methods.....	30
2.2.1	Introduction to Approximation Method and its improvement	30
2.2.2	Construction of outward refractive surface by point-by-point ray mapping	33
2.2.3	Construction of inward refractive surface by point-by-point ray mapping	33
2.2.4	Construction of TIR surface by point by point ray mapping	35
2.2.5	Construction of TIR surface with vertical wall	36
2.3	Design strategy for Illumination distribution by Point-by-point ray tracing method.....	37
2.3.1	Generation of surface construction seed curves with uniform magnification	37
2.3.2	Concept of non-linear Illumination surface generation.....	39
2.3.3	Generation of rotationally symmetric structured surfaces	39
2.3.3.1	Segmentation of input irradiance	40
2.3.3.2	Generation of seed curve:	42
2.3.3.3	Integration of structured surface segments:	43
2.3.3.4	Generation of 3D profile:	43
2.3.3.5	Ray trace simulation:	44
2.3.4	Generation of structured-freeform surfaces	44
2.3.4.1	Zonal segmentation of input irradiance distribution	44
2.3.4.2	Generation of orthogonal seed curves and Tilting	45
2.3.4.3	Tilt along one direction	46
2.3.4.4	Tilt along two axes (Euler angle rotation).....	47
2.3.4.5	Freeform element integration and use of aperture.	48
2.4	Design strategy for Structured optical element.....	48
3	Chapter 3: Optical design of IOL Edge profile to control Negative Dysphotopsia.....	49
3.1	Background.....	49
3.2	Optical model for Human Eye	50
3.2.1	Design and analysis tools	51
3.2.1.1	Ray fan charts.....	51
3.2.1.2	Spot diagram	51
3.2.2	Design of human eye with IOL	51

3.2.2.1	Human Eye Schematic with $R_1=R_2$, Biconvex spherical IOL	51
3.2.2.2	Human Eye Schematic with $R_1<R_2$, Biconvex spherical IOL	53
3.2.2.3	Human Eye with $R_1<R_2$, and conic K_2	54
3.3	Illustration of Negative Dysphotopsia in eye optical model	55
3.4	Correction method for Negative Dysphotopsia.....	58
3.4.1	Design strategy for generation of edge profile	58
3.5	Design strategy.....	59
3.5.1	Mathematical formulation for calculation of freeform edge profile	59
3.5.2	Magnification function.....	61
3.5.2.1	Constant magnification	62
3.5.2.2	Linearly reducing magnification	62
3.5.2.3	Non-linearly reducing magnification	62
3.5.2.4	Non-linear generalized variation of magnification	63
3.5.3	Process of freeform edge profile customization.....	64
3.5.4	Design validation.....	65
3.5.4.1	Ray trace analysis using B-type rays	65
3.5.4.2	Ray trace analysis using all types of rays.....	66
3.6	Conclusion	67
4	Chapter 4: Structured-freeform illuminator for laser display application	69
4.1	Background.....	69
4.2	Design strategy for laser spot illuminator	70
4.3	Bi-prism laser spot illuminator	71
4.4	Sleek Design	72
4.5	Comparison with condensing lens solution.....	74
4.6	Dispersion and chromatic aberration	75
4.7	Applications	76
4.7.1	Projection engine using light tunnel and laser spot illuminator	76
4.7.2	Projection engine using pair of lens-let array and laser spot illuminator.....	77
4.8	Simulation results.....	78
4.9	Prototype	80
4.10	Conclusions.....	83
5	Chapter 5 Structured and Structured-Freeform for LED Illumination Application.....	85
5.1	Background.....	85
5.2	Design modification in LED collimator.....	87

5.3	Design evaluation parameters	89
5.4	Collimator performance evaluation	89
5.5	Comparison with conventional collimator	93
5.6	Freeform beam shaping optical element for LED illumination	94
5.7	Structured surface for uniform illumination application.....	95
	<i>Problem statement:</i>	95
5.7.1	Segmentation.....	95
5.7.2	Search for seed points and element surface generation	96
5.7.3	Ray trace simulation.....	97
5.8	Structured surface for inverse funnel illumination.....	98
	<i>Problem statement:</i>	98
5.8.1	Segmentation.....	99
5.8.2	Search for seed points and element surface generation	99
5.8.3	Ray trace simulation.....	99
5.8.4	Funnel illuminations distribution	100
5.8.5	Result and discussion:	101
5.9	Structured-freeform surface for LED display application.....	101
	<i>Problem statement:</i>	101
5.9.1	Design scheme	101
5.9.2	Ray trace simulation.....	105
5.9.3	Result and Discussion.....	107
6	Chapter 6: Error estimation due to approximations in Shack-Hartmann sensor-based measurement of high slope freeform wavefront.....	109
6.1	Background	109
6.2	Basic principle for wavefront reconstruction	111
6.3	Design of SHS setup	112
6.4	Design strategy.....	112
6.5	SHS measurements setup by using Zemax Optical Design Tool.....	114
6.6	Wavefront reconstruction calculation.	116
6.6.1	Sag of input wavefront.....	116
6.6.2	Beam launch angle calculation	117
6.7	Wavefront reconstruction.....	119
6.8	Result and Discussion	120
6.9	Conclusion	122

Chapter 7: Conclusion and future scope of the research work	123
References	125
List of publications.....	134
Curriculum Vitae	136

List of figures

Figure 1.1 Surface generated by Reference [8] are termed as freeform element however, surface is similar to the part of cartesian curvature, or toroidal shape.	2
Figure 1.2 Technology space and market area of freeform optics.....	5
Figure 1.3 Use of freeform lens for hard-to-reach areas through light guides [29].....	6
Figure 1.4: High precision polishing process: Zeeko precession process polishing.....	8
Figure 1.5: First 14 terms of Zernike polynomial basis functions.[Ref [46, 46]].....	17
Figure 1.6 Improvement done by Gonzalez-Acuna et al. Using bi-spherical singlet free from spherical aberrations(right). The earlier solution shows discontinuity for some specific cases (left) [25].....	21
Figure 2.1(left) Outward refraction on the denser to rarer medium for collimated refracted rays, (right) Sequential calculation of locus point using Simple approximation method.....	32
Figure 2.2 (Left) Illustration for the nominal approximation method [9]. (Right) Effect of accumulation errors in Nominal Approximation Method.....	32
Figure 2.3(Left) Illustration for the modified approximation method [9]. (Right) locus points for modified approximation method.	33
Figure 2.4: (Left) Illustration for inward refraction using modified approximation method. (Right) Sequential calculation of locus point using a modified approximation method	34
Figure 2.5: (Left) Illustration for TIR surface calculation with hemispherical first surface. (Right) Sequential calculation of TIR locus point using	35
Figure 2.6: (Left) Illustration for TIR surface calculation with vertical wall at first surface. (Right) Sequential calculation of TIR locus point using	37
Figure 2.7(Left) Sequential calculation of the surface for prescribed irradiance redistribution. (Right) Sequential calculation of surface for prescribed energy distribution	39
Figure 2.8: Illustration of 3 cases: Case 1 when seed point is at the beginning of planes, Case 2: Seed point at intermediate position, Case3: when on axial seed point is not possible.	41
Figure 2.9. Illustration of re-arrangement of coordinates for case2 where seed points lie between within input plane but not at the extreme points. A) initial calculated coordinate for the curve, B) left side 3 mm length curve re-arranged, and C) 2mm	43
Figure 2.10: Example of curve generation (C1 and C2) for two segment k_1 and k_2	43
Figure 2.11 First step of the generation of freeform surface with different optical power in orthogonal direction. Here the input and output planes are along the optical axis of the surface.	46
Figure 2.12 Formation of the complete freeform element with the first (flat) and second (freeform) surface. Desirable tilts are given to the first and second surfaces such that the image reached the target plane off-axially. Here, the element as a whole tilted in one direction.	46
Figure 2.13 (Left) Formation of the freeform surface and (Right) complete freeform element with first (flat) and second (freeform) surface tilted according to Euler angle rotation.	47

Figure 2.14 [Left) Illustration of irradiance segmentation into zones ,(Center) aperture and (left) structured-freeform element	48
Figure 3.1: Historical survey of schematic Human Eye. Few main models are shown along with the parameters used in the design.	50
Figure 3.2. Performance of Human Eye for Normal, 0.4mm shifted IOL and a rotated compensated configuration for 2, 4, and 6 mm Iris size for a biconvex with equal radiuses..	52
Figure 3.3: Performance of Human Eye for Normal, 0.4mm shifted IOL and eye ball rotated compensated configuration for 2, 4, and 6 mm Iris size for biconvex with unequal radius. ...	53
Figure 3.4. Performance of Human Eye for Normal, 0.4mm shifted IOL and eye ball rotated compensated configuration for 2, 4, and 6 mm with biconvex, and second surface has conic section.	54
Figure 3.5. Summary of MTF values for spherical biconvex, convex spherical and aspheric biconvex lens and normal, shifted IOL and rotated eye ball configuration with 2mm, 4mm and 6mm pupil size.	55
Figure 3.6: Schematic diagram of pseudophakic eye with IOL depicting different path of rays (A, B, C and D) and resultant illumination on the retinal plane as ND region where shadow occurs. Table (on the side) list optical parameters used in modelling	56
Figure 3.7: Ray tracing with respect to various field angles of incidences in pseudophakic eyes. Iris= 5mm, reference point 3mm from cornea vertex, ray bundle width 1mm, the ray angles are taken form optic axis.....	57
Figure 3.8: Zemax ray tracing with respect to various angles of incidences in pseudophakic eyes. Iris= 5mm, reference point 3mm from cornea vertex, single ray. In closeup, three scenarios of ray refraction are depicted.	57
Figure 3.9: The effect on shadow region width for the combination of parameters IOL shift, pupil size, keppa angle and ray launching reference. The is based on angular scanning of higher angle fields using single ray tracing.	59
Figure 3.10Schematic of point-by-point ray mapping method for generation of tailor-made freeform profile. Length of reference plane (l) and target plane (L) is shown. Illustration for calculation of coordinates for freeform profile and iterative process.	61
Figure 3.11. (a) Constant magnification resulting into (b) equidistance ray distribution on the target plane.....	62
Figure 3.12. (a) linearly reducing magnification resulting into(b) gradually concentrating ray distribution on target plane.	62
Figure 3.13. (a) Non-linearly reducing magnification resulting into (B) highly concentrating ray distribution on target plane	63
Figure 3.14. (a) Non-linearly varying generalized magnification resulting into (b) high concentrating ray distribution at the intermediate position on the target plane	64
3.15. (a) Location of input and target plane in human eye schematics, (b) Input parameter for edge profile generation	64
Figure 3.16. 2D coordinate locus of developed edge profiles with respect to four different magnification functions.	65
Figure 3.17(a-c) Three possible elements using freeform edge profile for redistribution of light in shadow region. Haptics are also shown for illustration purpose. (d) Position of freeform elements, reference and target plane are used for design and validation of f	65

Figure 3.18. Validation of the freeform edge profile for the redistribution of B-type rays (collimated) at the target plane. Irradiance cross-section at target plane is shown with and without element.....	66
Figure 3.19Illumination intensity distribution on target plane illuminated by only B, C and D - type rays in a pseudophakic without freeform element. Cross section of illumination Negative and Positive Dysphotopsia regions (due to C -type rays).....	67
Figure 3.20. Irradiance redistribution on target plane illuminated by only B, C and D type ray bundles in a pseudophakic eye with and without freeform edge profile element.....	67
Figure 4.1: Geometrical ray diagram for calculation of prism angle τ for individual laser beam Geometrical ray diagram for calculation of prism angle τ for individual laser beam....	70
Figure 4.2: Sequential schematic for focusing of 2D array of collimated laser beams (4x4) using one and two dimensional prism elements; (a) Focusing of all vertical beams in one column by P ₁ , (b) Focusing of all horizontal beams in one row by P ₂ , and (c) Focusing in two dimensions by P ₁ and P ₂ in tandem.....	72
Figure 4.3: (a) Orthogonally arranged prism assembly with air gap; for 4x4 laser arrays.	72
Figure 4.4: (a) Orthogonally arranged prism assembly with air gap; for 4x4 laser arrays. (b) Compact Bi-prism laser spot illuminator assembly without air gaps.	73
Figure 4.5: laser spot illuminator Sleek design with line sources meeting away at 70mm target spot.....	73
Figure 4.6: Simulated optical elements for focusing of 16 collimated laser beams at 70mm away, case a) Spherical lens, b) Aspheric lens, and c) Laser spot illuminator. Here detectors are at the focus (small detector), and slightly out of focus (bigger detector) are showing incoherent illumination pattern.	75
Figure 4.7: laser spot illuminator (1 and 2) used in Light tunnel based projection engine with laser and hybrid primary light sources.....	76
Figure 4.8: laser spot illuminator used in lens-let based projection engine with laser and hybrid primary light sources.	77
Figure 4.9: Normalized Illumination cross section at image modulation plane for the projector design using laser spot illuminator and light tunnels.....	79
Figure 4.10: Normalized illumination cross section at image modulation plane for the projector design using laser spot illuminator and lens-let arrays.....	80
Figure 4.11: 2x4 laser spot illuminator manufacturing dimensions with subassembly -parts and glued actual proto-type.....	81
Figure 4.12: Orthogonal views of ray trace setup for verification of laser spot illuminator used for array of 2x4 collimated He-Ne laser beams (632.8nm). Intermediate observation planes are shown as D1, D2, and D3.	81
Figure 4.13: Simulated pattern at detector D1, D2 and D3 for 8 laser red laser beams passing through 4x2 Bi-prism model.....	82
Figure 4.14: Experimental verification of 4x2 Bi-prism prototype images at D1, D2, and D3 positions taken by camera. Inset shows detailed CCD camera image of the spot.	82
Figure 4.15: Statistics for 1000 random generated systems as per Monte Carlo method of tolerance analysis.	83
Figure 5.1. Schematic of freeform Type I collimator, where 1. Hemispherical surface, 2 TIR, 3 refractive surface, and 4 & 5 are not used in calculation.....	86

Figure 5.2. The schematic for the construction of Surface ‘3’ toward source side along with 2D model of Type II configuration.....	87
Figure 5.3: The geometry for the construction of Surface ‘2’ in the presence of vertical wall at Surface ‘1’ along with Zemax model of Type III configuration.....	88
Figure 5.4: Freeform collimation lens of Type I, II, and III with respective irradiance distribution on detector at 150 mm away from light source	90
Figure 5.5: Geometrical efficiency for different types of collimator Vs Source sizes	91
Figure 5.6. Illumination patterns and corresponding geometrical efficiencies for Type I, II & III collimator (In rows) for different source sizes i.e. point source, 0.5x0.5 mm ² , 1x1 mm ² , 1.5x1.5 mm ² , and 2x2 mm ² (along Columns)	91
Figure 5.7: Angular distribution at detector plane for different source sizes and collimator types, ie a) Type 1, b) Type II, and c) Type III.....	92
Figure 5.8 Conventional spherical multi-element collimation optics, irradiation distribution, and angular distribution for various LED source sizes.....	94
Figure 5.9. Segmentation of input irradiance distribution at exist plane of Type III collimator illuminated with 1x1 mm ² LED emitter. Table shows length of 6 segments.....	96
Figure 5.10. Section of segments without vertical offsets	97
Figure 5.11. (Left) 2D coordinates of structured-freeform surface locus. (Right) A solid 3D model of the designed structured -freeform element for uniform irradiance distribution	97
Figure 5.12. Zemax model of freeform element (left) with ideal collimated point source, (Right) with 1x1 mm ² area of LED emitter, Type-III collimator and freeform element	98
Figure 5.13. Irradiance distribution at input (Type-III collimator output) and output with and without the designed surface element on the top of Type-III LED collimator.	98
Figure 5.14. Segmentation of input irradiance distribution at exist plane of Type III collimator illuminated with 1x1 mm ² LED emitter. Table shows length of 8 segments.	99
Figure 5.15. (Left) 2D coordinates of freeform surface locus for all the segments after application of offset in x and y direction. (Right) A solid 3D model of the freeform element.	100
Figure 5.16. Irradiance distribution at the target plane before and after application of designed element on the top of Type III collimator.....	101
Figure 5.17:(Left) Spatial illumination distribution at the exit plan of Type-III collimator with 1x1mm ² LED light source area. The area is divided into 17 Zones to be used for the generation of 17 freeform elements. Due to mirror symmetry calculation of only nine elements is required (solid lines), other 8 zones (dotted lines) can be used with mirror operation on corresponding elements. The part outside this zone does not contribute to the output illumination; hence these parts of illumination are restricted by applying a proper aperture stop.(Right): Active area and Overfill dimension of image modulator.	104
Figure 5.18 Spatial illumination distribution at the exit plan of Type-III collimator with 1x1mm ² LED light source area with additional four zones at off-axial position is shown in red boxes. This zonal segmentation is used in the design of LED projector illumination with a smaller track length.....	105
Figure 5.19: Structured freeform element with central and off-axial elements (left), aperture to block non-zonal and stray light (centre) and structured-freeform element as projection illumination optics	106

Figure 5.20 Configuration 2, Freeform element, aperture, and Display illumination with LED light source, light collection structured optics, beam shaping structured freeform element and image modulation plan.....	106
Figure 5.21 Effect of LED light source emitting area on system and component efficiency (Right) and uniformity with two configurations config1= 210mm and config2=110mm track length	108
Figure 6.1: (a) Principle of Shack-Hartmann Sensor, (b) regular equidistance focus spot pattern with plane wave and (c) deviated focus spot pattern from distorted wavefront	111
Figure 6.2 : a) wavefront reconstruction flow chart b)Sub-aperture measurement by SHS scanning	112
Figure 6.3: Schematics of SHS design for steep slope wavefront generation.	114
Figure 6.4: Schematic of beams launched under Tilted Plane Wavefront (TPWF) approximation in SHS. The defocusing due to aspherical aberration is exaggeratedly depicted.	115
Figure 6.5: Schematic of beams launched under segmented Tilted Curved Wavefront (TCWF) approximation in SHS, the defocusing due to aspherical aberration is exaggeratedly depicted.....	115
Figure 6.6: Flow chart for wavefront reconstruction error calculation for various configuration.	116
Figure 6.7: (a) Sag of input full wavefront , (b) one quarter part of sag used for ray tracing in order to perform fast calculations.	117
Figure 6.8. Calculation of azimuthal and polar tilt angles for the ray launching on the vertex of lenslet at position (x,y).	118
Figure 6.9: Shift in centroid due to wavefront departure from the reference for a spherically diverging source at 150mm from the lenslet surface and thickness of 1.19mm under TPWF approximation. Here each small cube is the area of the individual lenslet.....	118
Figure 6.10: Input wavefront sag (approximate 50 waves) and respective reconstructed wavefront errors in TPWF and TCWF configuration. The row 1-4 shows data for lenslet thicknesses i.e. 1.19mm, 0.5mm, 0.2mm and, 0.005mm respectively.	120
Figure 6.11: Peak to Valley wavefront reconstruction error and dependency on lenslet thickness for TPWF.	121
Figure 6.12: Variation of wavefront reconstruction errors at three focal planes.	121

List of tables

Table 1-1. Survey of typical freeform surface generation methods and classification.....	27
Table 4-1: laser spot illuminator schematic for 1-D multiple collimated laser system.	71
Table 4-2: Geometrical arrangement of multiple Lasers and prisms arrangement with clear aperture shown by dotted lines.	74
Table 4-3: Details of optics elements and their performance.	75
Table 4-4: Light tunnel-based projector design performance (Figure 4.7).....	78
Table 4-5: Pair of lens-let array-based projector design performance (Figure 4.8).....	78
Table 4-6: List of worst offenders for a given set of tolerance values	79
Table 5-1: Image modulator dimensions	101
Table 5-2: Calculation of optical element for different zones and with z position and surface tilt angles.....	102
Table 5-3: Dimension (Length and width) of object and image, Nature of element in the orthogonal direction, and shape of the corresponding optical element.	103
Table 5-4 Configuration 1 ray tracing with 5 Million rays for various source sizes. Across section plot, active area irradiance map, and uniformity and efficiency (absolute and relative) listed. In irradiance map per color-band is equivalent to 2% variation.	106
Table 5-5 Configuration 2 (smaller track length) ray tracing with 5 Million rays for various source sizes. Across section plot, active area irradiance map and uniformity and efficiency (absolute and relative) listed. In irradiance map per color-band is equivalent	107

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	Diffraction 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