

**ULTRA-PRECISION DIAMOND TURNING PROCESSES
FOR THE FABRICATION OF FREEFORM AND
HYBRID OPTICS FOR IMAGING AND
COMMUNICATION APPLICATIONS**

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***Dedicated to parents, my family, and
teachers....!***

Certificate

This is to certify that the thesis entitled “**ULTRA-PRECISION DIAMOND TURNING PROCESSES FOR THE FABRICATION OF FREEFORM AND HYBRID OPTICS FOR IMAGING AND COMMUNICATION APPLICATIONS**” submitted by **KUNDAN KUMAR PRASAD** to the Centre for Sensors, Instrumentation and Cyber-physical System Engineering, Indian Institute of Technology Delhi, for the award of the degree of **DOCTOR OF PHILOSOPHY**. This thesis is a bonafide record of the research carried out by him under our guidance and supervision. In our opinion, the thesis has reached the standards fulfilling the requirements for the submission relating to the degree.

The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Prof. Gufran Sayeed Khan

Centre for Sensors, Instrumentation and
Cyber-physical System Engineering (SeNSE)
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Date:

Place:

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Abstract

The aim of the research work is to develop fabrication processes for ultra-precision diamond turning machining of freeform and hybrid optical surfaces suitable for imaging and communication applications. System miniaturization is increasingly shaping next-generation optical systems used in hyperspectral instruments, infrared imaging systems, and communication systems. The miniaturization of optical systems is fundamentally driven by the development of freeform and hybrid optical surfaces capable of integrating multiple functionalities. Their integration not only reduces the overall size and weight of imaging and communication systems but also enhances system efficiency and performance. Various manufacturing methods, i.e., tool-based cutting (ultra-precision machining) and beam-based (lithography) processes, each encompassing a range of specialized technologies, have been developed. Nevertheless, the ultra-precision diamond turning machining (DTM) process is suitable for fabricating freeform and hybrid optics for wide application areas (visible-LWIR) in terms of improved surface roughness and dimensional accuracy with minimum fabrication cost compared to other methods. Among them, ultra-precision diamond turning machining with multi-axis configuration has enabled the fabrication of complex surface geometries with high precision. Despite these advancements, increasing the number of machining axes adds system complexity. Moreover, existing studies on hybrid optical surfaces primarily focus on feature sizes greater than 10 μm . Hybrid optical surfaces with feature sizes less than 5 μm are crucial for high-performance imaging applications, yet their precise fabrication on curved geometries remains challenging. Furthermore, surface quality optimization in brittle materials like single-crystal germanium is insufficiently explored, particularly in understanding slow tool servo (STS) based diamond turning machining parameters of freeform optics for an infrared imaging system. In addition to visible and infrared imaging applications, visible light communication (VLC) systems require compact and efficient optical receiver front-ends. Freeform Fresnel and monolithic optics provide superior light collection and aberration control, yet their intricate structures pose fabrication challenges. Ultra-precision diamond turning offers a viable solution for machining such components with high precision. Addressing these research gaps is critical for advancing ultra-precision diamond turning and enabling next-generation imaging and communication technologies.

This thesis presents the work on the development of ultra-precision diamond turning machining (DTM) processes for the fabrication of hybrid optical surfaces, essential for next-generation

imaging and communication technologies. The thesis is summarized in the following four major investigations:

- a) Experimental investigations on rotationally symmetrical hybrid optical (concentric grating on the curved profile) surfaces.
- b) Ultra-precision diamond turning of curved gratings for hyperspectral imaging optics.
- c) An intelligent approach for optimizing process parameters in diamond turning of single crystal germanium (sc-Ge), along with an investigation of ductile machining of sc-Ge freeform optics for infrared imaging.
- d) The development of non-rotationally symmetrical, monolithic freeform Fresnel optics to enhance compact visible light communication (VLC) receiver front-ends.

In the first study, a novel retract toolpath strategy for fabricating rotationally symmetrical hybrid optics (micro-concentric grooves on the curved surface), enabling precise dual-profile machining with uniform micro-grooves and minimal form errors, has been presented. A hybrid surface with 5 μm features on a 38 mm radius sphere profile was successfully fabricated. Compared to conventional methods, the approach offers enhanced control over feature size, pitch, and groove depth. Its effectiveness was established on materials like aluminum, brass, and PMMA, demonstrating its suitability for consistent microstructuring on curved surfaces in diverse applications.

In the second study, the development of rotationally symmetrical hybrid surfaces, focusing on linear gratings on curved surfaces, which are crucial for compact hyperspectral imaging systems, has been carried out. However, fabricating the linear gratings on curved surfaces posed challenges due to the lack of direct machining approaches in existing software. To overcome this, a customized fixture and a particularly developed toolpath that has been detailed in the first study were employed. Building on this approach, the study was further extended to develop grating profiles on toric surfaces using the same fixture and toolpath. These advancements enhance precision machining, foster innovation in micro-manufacturing, and support the industry's growing demand for component miniaturization and performance optimization.

In the third study, an in-depth investigation into the fabrication of high-quality optics on single-crystal germanium (sc-Ge), a brittle material widely utilized in infrared (IR) applications, has been presented. The study is systematically divided into two key sections, each addressing critical aspects of machining and optimization to enhance the surface quality and precision of sc-Ge optics. The first part of the study focuses on improving the surface finish of sc-Ge flat

optics using a diamond turning machine (DTM). A response surface methodology (RSM) with a teaching-learning-based optimization (TLBO) algorithm has been used. The insights gained from this phase are further leveraged as evaluation criteria for generating freeform optics. The second part of the study focuses on fabricating cubic phase freeform optics on sc-Ge for IR imaging systems, where thermal-induced defocus is a critical issue. This investigation not only provides a deeper understanding of the brittle-to-ductile transition in sc-Ge machining but also advances nano-surface generation techniques, ultimately contributing to the enhancement of fabrication processes for high-performance IR freeform optics.

In the fourth study, the fabrication strategies based on the slow tool servo configuration of diamond turning for the development of novel freeform Fresnel, i.e., single freeform Fresnel and monolithic freeform Fresnel surfaces for the receiver unit of visible light communication systems, have been developed. The STS cutting strategies, mainly constant angle and hybrid approaches, have been considered to study its impact on the generation of freeform Fresnel profiles. These strategies have been further applied to investigate its effects on the substrate position with respect to the vacuum chuck of diamond turning. Furthermore, the fabricated surface has undergone performance evaluation as a front-end Li-Fi receiver unit.

It is expected that the investigations carried out in the thesis work will help in substantially increasing the accuracy of the production of high-performance freeform and hybrid optics for imaging and communication applications.

सारांश

इस शोध कार्य का उद्देश्य इमेजिंग और संचार अनुप्रयोगों के लिए उपयुक्त, फ्रीफॉर्म और हाइब्रिड ऑप्टिकल सतहों की अल्ट्रा-प्रिसिजन डायमंड टर्निंग मशीनिंग हेतु निर्माण प्रक्रियाएँ विकसित करना है। सिस्टम का लघुकरण (मिनिचराइज़ेशन) अगली पीढ़ी के ऑप्टिकल सिस्टम के विकास में सहायता कर रहा है, जिनका उपयोग हाइपरस्पेक्ट्रल उपकरणों, इन्फ्रारेड इमेजिंग सिस्टम और संचार प्रणालियों में किया जाता है। ऑप्टिकल प्रणालियों का लघुकरण मूलतः उन फ्रीफॉर्म और हाइब्रिड ऑप्टिकल सतहों के विकास से प्रेरित है, जो अनेक कार्यक्षमताओं को एकीकृत करने में सक्षम हैं। इनका एकीकरण न केवल इमेजिंग और संचार प्रणालियों के समग्र आकार और वज़न को कम करता है, बल्कि प्रणाली की दक्षता और प्रदर्शन को भी बढ़ाता है। विनिर्माण के विभिन्न तरीके-जैसे कि टूल-आधारित कटिंग (अति-सटीक मशीनिंग) और बीम-आधारित (लिथोग्राफी) प्रक्रियाएँ-विकसित किए गए हैं, जिनमें से प्रत्येक में विशेष तकनीकों की एक विस्तृत श्रृंखला शामिल है। फिर भी, अल्ट्रा-प्रिसिजन डायमंड टर्निंग मशीनिंग प्रक्रिया, अन्य तरीकों की तुलना में न्यूनतम निर्माण लागत पर बेहतर सतह खुरदरापन और आयामी सटीकता के मामले में, व्यापक अनुप्रयोग क्षेत्रों (दृश्य-दीर्घ तरंग इन्फ्रारेड) के लिए फ्रीफॉर्म और हाइब्रिड ऑप्टिक्स बनाने के लिए उपयुक्त है। इनमें से, मल्टी-एक्सिस कॉन्फिगरेशन वाली अल्ट्रा-प्रिसिजन डायमंड टर्निंग मशीनिंग ने उच्च सटीकता के साथ जटिल सतह ज्यामितियों के निर्माण को संभव बनाया है। इन प्रगतियों के बावजूद, मशीनिंग अक्षों की संख्या बढ़ाने से सिस्टम की जटिलता बढ़ जाती है। इसके अलावा, हाइब्रिड ऑप्टिकल सतहों पर मौजूदा अध्ययन मुख्यतः 10 माइक्रोन से बड़े फीचर आकारों पर केंद्रित हैं। 5 माइक्रोन से कम फीचर आकार वाली हाइब्रिड ऑप्टिकल सतहें उच्च-प्रदर्शन इमेजिंग अनुप्रयोगों के लिए अत्यंत महत्वपूर्ण हैं, लेकिन वक्र सतहों पर उनका सटीक निर्माण अभी भी चुनौतीपूर्ण है। इसके अतिरिक्त, सिंगल-क्रिस्टल जर्मेनियम जैसे भंगुर पदार्थों में सतह गुणवत्ता का इष्टीकरण पर्याप्त रूप से अध्ययनित नहीं है, विशेषकर इन्फ्रारेड इमेजिंग सिस्टम के लिए फ्रीफॉर्म ऑप्टिक्स की स्लो टूल सर्वो (STS) आधारित डायमंड टर्निंग मशीनिंग पैरामीटर की समझ में। दृश्य और इन्फ्रारेड इमेजिंग अनुप्रयोगों के अलावा, दृश्य प्रकाश संचार (VLC) प्रणालियों को कॉम्पैक्ट और कुशल ऑप्टिकल रिसीवर फ्रंट-एंड्स की आवश्यकता होती है। फ्रीफॉर्म फ्रेसनेल और अखंड ऑप्टिक्स बेहतर प्रकाश संग्रहण और विपथन नियंत्रण प्रदान करते हैं, फिर भी उनकी जटिल संरचनाएँ निर्माण संबंधी चुनौतियाँ खड़ी करती हैं। अल्ट्रा-प्रिसिजन डायमंड टर्निंग ऐसे घटकों के उच्च-सटीकता निर्माण के लिए एक व्यवहार्य समाधान प्रदान करता है। इन शोध अंतरालों को संबोधित करना अल्ट्रा-प्रिसिजन डायमंड टर्निंग को आगे बढ़ाने और अगली पीढ़ी की इमेजिंग तथा संचार तकनीकों को सक्षम बनाने के लिए अत्यंत महत्वपूर्ण है।

यह शोध प्रबंध (थीसिस) हाइब्रिड ऑप्टिकल सतहों के निर्माण के लिए अल्ट्रा-प्रिसिजन डायमंड टर्निंग मशीनिंग प्रक्रियाओं के विकास पर आधारित है, जो अगली पीढ़ी की इमेजिंग और संचार तकनीकों के लिए आवश्यक हैं। इस थीसिस को निम्नलिखित चार प्रमुख अध्ययनों में संक्षेपित किया जा सकता है:

अ) घूर्णन सममित (rotationally symmetric) हाइब्रिड ऑप्टिकल (वक्र प्रोफ़ाइल पर समकेंद्रीय ग्रेटिंग) सतहों पर प्रायोगिक अध्ययन।

ब) हाइपरस्पेक्ट्रल इमेजिंग ऑप्टिक्स के लिए वक्र ग्रेटिंग्स की अति-सटीक (अल्ट्रा-प्रिसिजन) डायमंड टर्निंग।

स) सिंगल-क्रिस्टल जर्मेनियम (sc-Ge) की डायमंड टर्निंग में प्रक्रिया पैरामीटर के इष्टीकरण हेतु एक अभूतपूर्व दृष्टिकोण, तथा इन्फ्रारेड इमेजिंग के लिए sc-Ge फ्रीफॉर्म ऑप्टिक्स की डक्टाइल मशीनिंग का अध्ययन।

द) कॉम्पैक्ट दृश्य प्रकाश संचार (VLC) रिसीवर फ्रंट-एंड्स को बेहतर बनाने के लिए, घूर्णन-असममित, अखंड फ्रीफॉर्म फ्रेसनेल ऑप्टिक्स का विकास।

पहले अध्ययन में, घूर्णन सममित हाइब्रिड ऑप्टिक्स (वक्र सतह पर सूक्ष्म-संकेन्द्रित खांचे/ग्रूव्स) के निर्माण के लिए एक नई रिट्रैक्ट टूलपाथ रणनीति प्रस्तुत की गई है, जो एकसमान सूक्ष्म-ग्रूव्स और न्यूनतम आकार त्रुटियों के साथ सटीक दोहरे-प्रोफ़ाइल के निर्माण को संभव बनाती है। 38 मिमी त्रिज्या वाले गोलाकार प्रोफ़ाइल पर 5 माइक्रोन फीचर वाली एक हाइब्रिड सतह सफलतापूर्वक निर्मित की गई। परंपरागत विधियों की तुलना में, यह प्रक्रिया फीचर के आकार, पिच और ग्रूव गहराई पर बेहतर नियंत्रण प्रदान करती है। इसकी प्रभावशीलता एल्यूमिनियम, पीतल और PMMA जैसे पदार्थों पर स्थापित की गई, जो विभिन्न अनुप्रयोगों में वक्र सतहों पर समान माइक्रो-संरचना निर्माण के लिए इसकी उपयुक्तता दर्शाती है।

दूसरे अध्ययन में, वक्र सतहों पर रैखिक ग्रेटिंग्स पर केंद्रित, घूर्णन सममित हाइब्रिड सतहों का विकास किया गया है, जो कॉम्पैक्ट हाइपरस्पेक्ट्रल इमेजिंग प्रणालियों के लिए अत्यंत महत्वपूर्ण हैं। हालांकि, वक्र सतहों पर रैखिक ग्रेटिंग्स का निर्माण मौजूदा सॉफ्टवेयर में प्रत्यक्ष मशीनिंग विधियों की कमी के कारण चुनौतीपूर्ण था। इस समस्या को हल करने के लिए, एक कस्टमाइज़्ड फिक्स्चर और पहले अध्ययन में विकसित विशेष टूलपाथ का उपयोग किया गया। इस दृष्टिकोण के आधार पर, अध्ययन को आगे बढ़ाकर टोरिक (toric) सतहों पर ग्रेटिंग प्रोफ़ाइल विकसित की गई। ये प्रगति सटीक मशीनिंग को बढ़ावा देती हैं,

माइक्रो-मैक्युफैक्चरिंग में नवाचार को प्रोत्साहित करती हैं, और उद्योग की बढ़ती लघुकरण तथा कार्यक्षमता इष्टमीकरण की मांग को समर्थन देती हैं।

तीसरे अध्ययन में, सिंगल-क्रिस्टल जर्मेनियम (sc-Ge) पर उच्च-गुणवत्ता ऑप्टिक्स के निर्माण का विस्तृत अध्ययन प्रस्तुत किया गया है, जो इन्फ्रारेड अनुप्रयोगों में व्यापक रूप से उपयोग होने वाला एक भंगुर पदार्थ है। इस अध्ययन को दो प्रमुख भागों में व्यवस्थित रूप से विभाजित किया गया है, जो sc-Ge ऑप्टिक्स की सतह गुणवत्ता और सटीकता को बढ़ाने के महत्वपूर्ण पहलुओं को संबोधित करते हैं। पहला भाग, डायमंड टर्निंग मशीन (DTM) का उपयोग करके sc-Ge समतल ऑप्टिक्स की सतह फिनिश में सुधार पर केंद्रित है। शिक्षण-अधिगम-आधारित इष्टमीकरण (Teaching-Learning-Based Optimization) एल्गोरिद्म के साथ एक प्रतिक्रिया सतह कार्यप्रणाली (Response Surface Methodology) का उपयोग किया गया है। इस चरण से प्राप्त अंतर्दृष्टियों को फ्रीफॉर्म ऑप्टिक्स के निर्माण के लिए मूल्यांकन मानदंड के रूप में उपयोग किया गया। इस अध्ययन का दूसरा भाग, इन्फ्रारेड इमेजिंग सिस्टम के लिए sc-Ge पर क्यूबिक फेज़ फ्रीफॉर्म ऑप्टिक्स के निर्माण पर केंद्रित है, जहाँ तापीय-प्रेरित डीफोकस एक गंभीर समस्या है। यह अनुसंधान न केवल sc-Ge मशीनिंग में 'भंगुर से तन्य संक्रमण' (brittle-to-ductile transition) की गहरी समझ प्रदान करता है, बल्कि नैनो-सतह निर्माण तकनीकों को भी उन्नत करता है; जिससे अंततः उच्च-प्रदर्शन वाले इन्फ्रारेड फ्रीफॉर्म ऑप्टिक्स की निर्माण प्रक्रियाओं को बेहतर बनाने में योगदान मिलता है।

चौथे अध्ययन में, डायमंड टर्निंग की 'स्लो टूल सर्वो (STS) कॉन्फ़िगरेशन' पर आधारित निर्माण रणनीतियाँ विकसित की गई हैं, जिनका उपयोग विजिबल लाइट कम्युनिकेशन सिस्टम के रिसीवर यूनिट के लिए नवीन फ्रीफॉर्म फ्रेनेल (एकल और मोनोलिथिक) सतहों के विकास में किया गया है। STS कटिंग रणनीतियाँ, मुख्यतः स्थिर कोण और हाइब्रिड विधियाँ, फ्रीफॉर्म फ्रेनेल प्रोफ़ाइल के निर्माण पर उनके प्रभाव के अध्ययन के लिए अपनाई गईं। इन रणनीतियों का उपयोग सब्सट्रेट की स्थिति (वैक्यूम चक के सापेक्ष) पर उनके प्रभाव की जांच के लिए भी किया गया है। इसके अतिरिक्त, निर्मित सतह के प्रदर्शन का मूल्यांकन रिसीवर फ्रंट-एंड के रूप में किया गया है। यह अपेक्षा की जाती है कि इस शोध कार्य में किए गए अध्ययन, इमेजिंग और संचार अनुप्रयोगों के लिए उच्च-प्रदर्शन फ्रीफॉर्म और हाइब्रिड ऑप्टिक्स के उत्पादन की सटीकता को यथार्थतः बढ़ाने में सहायक होंगे।

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List of abbreviations

VLC	Visible Light Communication
DTM	Diamond Turning Machining
STS	Slow Tool Servo
FTS	Fast Tool Servo
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
NURBS	Non-Uniform Rational B-Splines
UV	Ultraviolet
NIL	Nanoimprint Lithography
CMM	Coordinate Measuring Machine
NANOMEFOS	Non-Contact Measurement Machine for Freeform Optics Surfaces
SEM	Scanning Electron Microscopy
AFM	Atomic Force Microscopy
sc-Ge	Single-Crystal Germanium
PMMA	Polymethyl methacrylate
FESEM	Field Emission Electron Microscope
TLBO	Teaching-Learning-Based Optimization
RSM	Response Surface Methodology
ANOVA	Analysis of Variance
MRR	Material Removal Rate
SiC	Silicon Carbide
CCD	Center Composite Design
LWIR	Long-wave infrared
MTF	Modulation Transfer Function
CGH	Computer Generated Hologram
OPD	Optical Path Difference
SFF	Single Freeform Fresnel
MFF	Monolithic Freeform Fresnel
SNIR	Signal to Interference Plus Noise Ratio

List of symbols

$Z_{hybrid}(r)$	hybrid surface sagitta
$z_1(r)$	sag of the curved
$Z_2(r)$	groove depth
r	radial distance
c	curvature of the base sphere
k	conic constant
a_i	aspheric coefficients
N	order of the polynomials
a	contact radius
h	maximum groove depth
r_t	tool nose radius
p	pitch
w	feature sizes
D	diameter of a workpiece
s	spacing
R	radius of curvature
d	depth of cut
N	spindle speed
f	feed rate
F_{groove}	normal force
$\varepsilon(r)$	elastic deformation
Δd	Incremental depth
E_{eqv}	equivalent elastic module
r_{eqv}	equivalent radius
E_1, E_2	moduli of elasticity
ν_1, ν_2	poisson's ratios
$R_{effects}$	shadowing effects
θ_1	half of the included angle of the tool
h_c	critical chip thickness
d_c	surface damage depth
w_c	location of the ductile-brittle transition
H	hardness
k_c	fracture toughness
Sa	surface roughness

t_f	teaching factor
Φ	lens power
n	refractive index
$t_{transition}$	transition radius
α	thermal expansion coefficient
$\Delta\theta$	incremental angle
Δs	incremental arc length