

Title: Ultra-Precision Diamond Turning Processes for the Fabrication of Freeform and Hybrid Optics for Imaging and Communication Applications

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. The miniaturization of optical systems is fundamentally driven by the development of freeform and hybrid optical surfaces capable of integrating multiple functionalities. Ultra-precision diamond turning machining with multi-axis configuration has enabled the fabrication of complex surface geometries with high precision.

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. 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.