Chapter 7 Concluding Remarks

7.1. Introduction

Ophthalmic lenses are part of daily life—the reader either uses corrective lenses or knows someone who does. For the foreseeable future, this will be the case, and the art of ophthalmic lens design continues to advance to provide the best vision possible. The purpose of this research is to elucidate the use of gradient-index (GRIN) materials in ophthalmic lens designs. This is done both by demonstrating design methods and by advancing the understanding of GRIN copolymer fabrication.

Currently, spectacle lenses are designed and manufactured using the surface shapes as the primary design degrees of freedom—GRIN materials are not used. This is due to at least two reasons: a lack of thorough design methods and a lack of suitable GRIN materials. This research presents a broad, yet detailed, explanation of the design of ophthalmic lenses with gradient-index materials as the primary design parameter. Furthermore, it is shown that the methodology presented can be used for non-ophthalmic applications. Finally, to advance the material science, the fabrication of large Δn gradients is studied and modeled. These results are reviewed and potential areas for future research are identified.

7.2. Unifocal Lenses

7.2.1. Review

In Chapter 2, fundamental design principles for first-order, gradient-index ophthalmic lens design are presented and compared to similar principles for homogeneous, conicoidal lenses. The solution spaces for zero-astigmatism, zero-power error, and reduced distortion errors are calculated and presented. From there, GRIN designs for realistic design needs are illustrated and compared to the equivalent conicoidal lens designs. High curvature, low aberration lens designs using gradient-index parameters are then compared to similar aspheric designs. The reduction of lens thickness via GRIN materials is illustrated. These various cases show that GRIN designs provide equivalent performance as the aspheric designs.

7.2.2. Future Work

The next step towards practical realization of GRIN spectacle lenses is investigation of manufacturing concerns. Copolymer systems could be surveyed to assess which offer the necessary index change over the necessary lens radius. With the appropriate systems, GRIN lenses could be fabricated and tested to compare performance to theory. With fabricated lenses, clinical trials could also be run to see if there are any physiological factors that differ between GRIN spectacle lenses and their homogeneous counterparts.

7.3. Progressive Power Lenses

7.3.1. Review

Chapter 3 extends the work in Chapter 2 to GRIN design methods for progressive power designs. It is shown how a gradient-index profile can be determined which will provide an arbitrary power form. The calculation of aberrations is explained, and the means to minimize, or eliminate, the optical errors are presented. It is also shown that given a refractive index function, the sagittal and tangential powers can be determined. Both analytical and numerical methods to calculate the necessary index profile for a given power form are explained.

The rotationally symmetric designs of Chapter 3 are further generalized in Chapter 5, where the design of asymmetric designs are explained. A method for predicting the index profile for a progressive addition lens is explained for the first time. Two examples are presented and their performances evaluated. Their optical performance is examined and strengths and weaknesses discussed.

7.3.2. Future Work

The index prediction for the progressive power lenses works well near the axis for small gaze angles. However, the prediction is increasingly worse as gaze angle increases. This is because rays no longer intersect the index gradient parallel with the index isoclines, but at an ever steeper angle, and thus the effective local gradient deviates from the design profile. This effect must be accounted for to improve the theoretical prediction of index profiles for progressive power lenses.

Second, for progressive addition lenses, the aberrations in the mid-lateral sections must be reduced. This will be aided by the just suggested improvement in index prediction. But also needed is a robust algorithm for optimizing the index profile via ray-tracing simulation. The use of B-splines to represent the index profile promises to allow localized index manipulation, and thus allow optimization of localized regions. However, the implementation is non-trivial and must be further developed. It may also be useful to generalize the B-spline basis functions to use arbitrary patch sizes. Then fewer patches could be used in the distance region where the index is fairly constant, and more patches to be used in the transition region where the index changes most rapidly. This would provide more effective representation for a given number of control points.

Finally, in this research only the monovision aberrations were addressed. There still remain the binocular vision aberrations, and image fusion problems, caused by the two eyes looking through different portions of the lenses for off-axis horizontal angles.[1-3]

7.4. Gradient-Index Axicon

7.4.1. Review

In Chapter 4, the theory from Chapter 2 was used in a novel fashion to design an axicon, a non-imaging lens element with an extended foci. A GRIN axicon with its initial focus offset from the back surface was designed using the thin-lens approximation. Two samples were fabricated via the time varying boundary condition

(TVBC) diffusion method, which is based on the MQC diffusion model. Intensity profile measurements were taken along the focal region of the axicons. The samples produced extended line foci. From the intensity measurements, the central spot widths and back focal lengths were determined. The peak widths matched theoretical predictions made via diffraction theory for the samples and showed good agreement with the predicted widths for a pseudo-Bessel beam, showing that the axicon produced a pseudo non-diffracting beam. This demonstrates the broader applicability of the design methods of this research, as well as another use for GRIN materials.

7.4.2. Future Work

Since this is the first GRIN axicon fabricated, there is much work remaining to refine the design and fabrication processes. Designs for extended focal regions could be examined. The two axicons produced had focal region lengths of about 10 mm. It remains to be seen if this could be significantly increased or decreased; shorter focal lengths seem to be the greater challenge. It could also be determined whether the focal region could be made to start closer to the back surface. In addition, it could be of interest to study the use of GRIN axicons in appropriate systems, such as for optical coherence tomography.[4]

The performance of the GRIN axicons can be further improved, particularly in the beginning of the focal region. There, the beam behavior deviates most from the desired behavior and is likely caused by deviations in the fabricated index gradient from the desired gradient. Since the axicon is designed using a geometrical optics method, and axicons behave due to diffraction (wave) effects, it is reasonable to expect that a wave-based design of GRIN axicon could perform better.

Finally, these axicons were fabricated in a convenient GRIN glass, with no consideration to the optimal glass type. The choice of glass, and available index profile, could be investigated for further axicon improvements.

7.5. Gradient-Index Copolymers

7.5.1. Review

Many of the GRIN designs in Chapters 2, 4, and 5 have high Δn values, extending over a large spatial extent—much greater than can currently be achieved by ion-exchange diffusion in glass, or perhaps any other GRIN glass fabrication method. To advance the state of gradient-index profiles towards larger Δn values and larger diffusion depths, a known copolymer system is studied and described.

This is the first experimental model of styrene diffusing into a partially polymerized methyl-methacrylate gel. It is shown that the diffusion is Fickian with a constant diffusion coefficient. The diffusion depth achieved is over 30 mm, and the Δn is 0.09, for 632.8 nm, making this one of the largest Δn and deepest diffusion depths measured in a polymer system during the diffusion process.

7.5.2. Future Work

This research into GRIN polymer systems is the beginning of what could be a tremendous area for GRIN design and fabrication. With a Δn of nearly 0.1 and a diffusion depth of more than 40 mm, many designs previously impossible with GRIN glass now may be tenable. But the fabrication and diffusion models must be furthered.

Within the styrene and methyl-methacrylate copolymer, different mold geometries could be explored for different index geometries. A circular mold could be used for radial diffusions, for example. A creative design is required for a circular mold that allows the entire sample perimeter to be immersed in the diffusing monomer, while mounted in a measurement system—the system described here for axial diffusion would have to be significantly modified. The copolymer system could also be reversed—methyl-methacrylate diffusing into a styrene gel—to determine if the system works in the configuration and the opposite profile direction created.

Though the system studied here showed Fickian diffusion behavior, this is not always the case for polymers. And even with this system, it is unknown if this is the case for pre-polymerization times less-than or greater-than those used in this thesis. It is anticipated that as the pre-polymerization is increased, diffusion will become concentration dependent and eventually will become a non-Fickian process, but this remains to be determined.

Different polymer systems should also be examined.[5-14] Some systems may provide Δn values greater than 0.1, but it is unknown if these index gradients can be created over large distances. Also, a diffusion model of these over large distances remains to be developed in many cases.

Finally, of particular potential use to GRIN technology is the creation of custom index profiles by use of selective polymerization. Since polymerization can induced by exposure to ultraviolet light, the polymerization can be localized within a monomer by specific illumination patterns.[15] It should be examined how the diffusion process could be controlled by use of masking and selective pre-polymerization of the base monomer. And, if possible, descriptive models should be developed to allow for design-for-manufacture work.[16]

7.6. References

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