UV Curable Polymer Optics

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Abstract

Glass and polymer optics are used extensively in a variety of applications. Some uses for optics include; medical disposables, bar-code scan/recognition, security and finger print scanners, motion and presence sensors, rifle scopes, eye glasses, and CCD cameras. Polymer optics offer several advantages over traditional glass optics including lighter weight, ease of manufacturing, and lower material cost. Due to these advantages, optical glass materials have been successfully replaced with polymer optics in many applications such as eye glasses, phone screens, and cameras. Current drawbacks of polymer optics include the lack of a high precision fabrication method as well as limited materials that exhibit equivalent material properties to those of glass optics. There are an abundance of optical glass materials available for use in commercial optical systems and very limited optical polymer materials. In this study we explore a variety of different materials with a wide variation of refractive index and Abbe numbers to create a broader range of optical properties to choose from when designing polymer lenses. A plethora of different chemistries utilizing a comprehensive list of monomers will be investigated to create an expansive polymer materials library for the use in lens fabrication. The end goal is to create polymer optical materials for direct view sighting systems due to their lighter weight, lower material cost, and ease of manufacturing.

Introduction:

Polymer optics are not widely used due to their inability to obtain optical glass quality and physical properties from traditional chemistries. To increase the availability of polymer optics, step growth polymer reactions were used to form optics while minimizing aberrations formed from shrinkage and stress during the polymerization. In this study we focus on UV cured thiol-acrylate polymerization systems.

Background:

When designing optical systems two important parameters are Abbe number and birefringence. The Abbe number is the measurement of the material's dispersion. The higher the dispersion the lower the Abbe number. Abbe numbers ranges from 17 to 95 for moldable glasses. Abbe numbers lower than 55 are known as flint glass and have low dispersion and glasses with Abbe numbers higher than 55 are known as crown glass and have high dispersion. Both low and high Abbe numbers are needed as they have different commercial uses. Birefringence is the variation of refractive index with the polarized state of light. Low birefringence is preferred because this means the lens is uniform and has little variation throughout its surface. Birefringence is mostly induced by the injection molding process, which is a characteristic that UV curing will hopefully substantially reduce.

Chemistry Overview:

An extensive list of monomers was created as a starting point to obtain a wide range of refractive index and Abbe numbers for the polymer optics. Once the monomers were selected, Table 1 was constructed to summarize the pros and cons of each chemistry type that was being investigated. Figures 1, 2, 3, and 4 illustrate the mechanism for these chemistries.

Table 1: Types of chemistries and initiator types utilized to build a polymeric materials library

Chemistry Type	Catalyst	Descriptions of each category
Thiol-Ene Thiol-Acrylate	Photoinitiator	UV cured – need uniform irradiation. Step growth and/or chain growth reaction
Thiol-isocyanate	Base catalyzed	Thermally catalyzed – step growth reaction.
Thiol-Michael	Base catalyzed	Thermally catalyzed – step growth reaction
Thiol-epoxide	Base catalyzed	Thermally catalyzed – step growth reaction

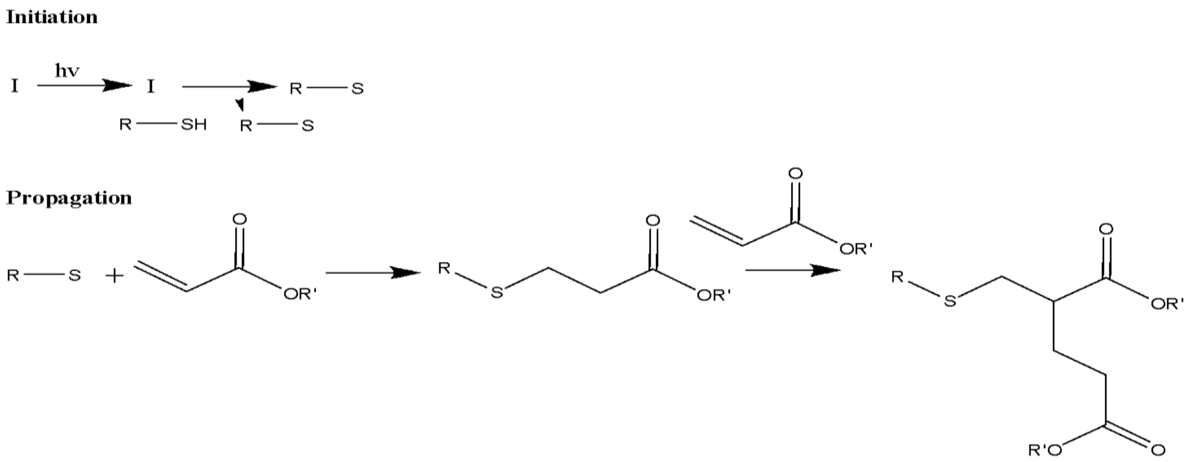


Figure 1: Thiol/Ene and Thiol/acrylate mechanism. The photoinitiator produces a radical upon absorption of light. The initiator radical abstracts a hydrogen from the thiol, transferring the radical to the thiol. The initiator radical can also propagate across double bonds. The thiol radicals propagate across the acrylate double bonds followed by a combination of both homopolymerization of the acrylate functional groups and chain transfer to thiol functional groups. This step-chain growth polymerization mechanism is the basis for the thiol-acrylate polymerization reaction. For the thiol-ene polymerization reaction, ene functional groups do not homopolymerize with other ene functional groups, instead participating only in chain transfer reactions with thiol functional groups for a purely step growth polymerization mechanism.

Molding Procedures:

Utilizing thiol/ene and thiol/acrylate UV curable systems allowed for screening of materials to obtain both crown and flint like polymer optics in a variety of different configurations. Molds were custom 3D printed and were designed to exhibit good flexibility to allow the mold to shrink with the polymer as it cured. This reduced the optical aberrations at the lens surface when removing the lens from the molds. After curing, the lenses were demolded by swelling the mold in isopropyl alcohol for 30 minutes. Figure 2 shows the various mold configurations that were custom 3D printed.

Figure 2: Various lens configurations. The space between the glass molds makes up the shape of the lens.

In addition to flat, concave, and biconvex lenses, doublets were also made as these are important in many applications due to their increase in focus. Figure 3 shows this shift in focus.

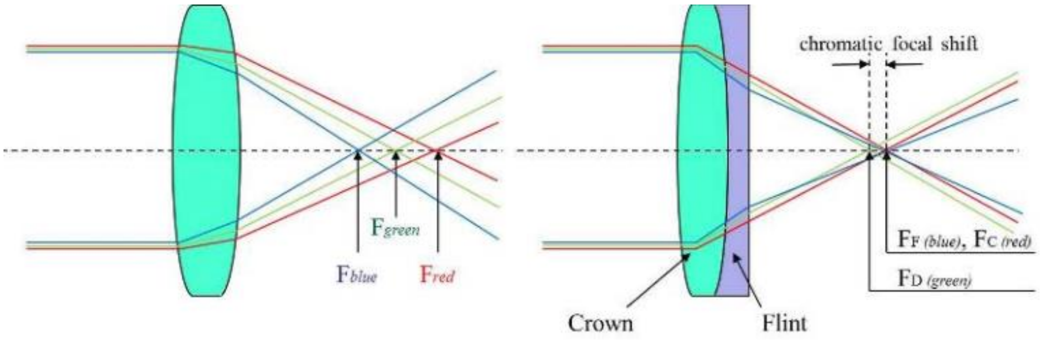


Figure 3: Singlet vs Doublet lens.

Although aspherical lenses were not fabricated in this study, they are important in the industry as it converges the focal point of the lens. Figure 4 shows this convergence of the focal point.

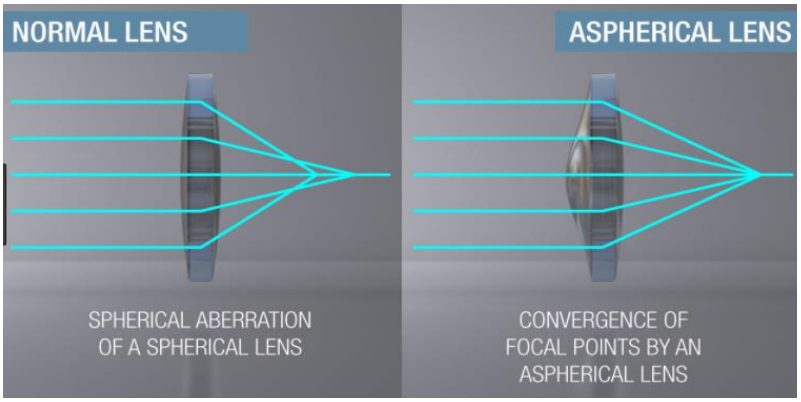


Figure 4: Spherical vs aspherical lens.

Curing Procedures:

Upon initial curing of the molds, it was evident that uneven and rapid curing was causing poor optical quality. Using a thermocouple, the resin temperature was shown to rise by 30 °C in the first 5 seconds of curing and rose over 100 °C within 20 seconds. Thermal imaging was used to monitor if the heat evolution was uniform or if hot spots were seen. Figure 5 indicated hot spots throughout the mold

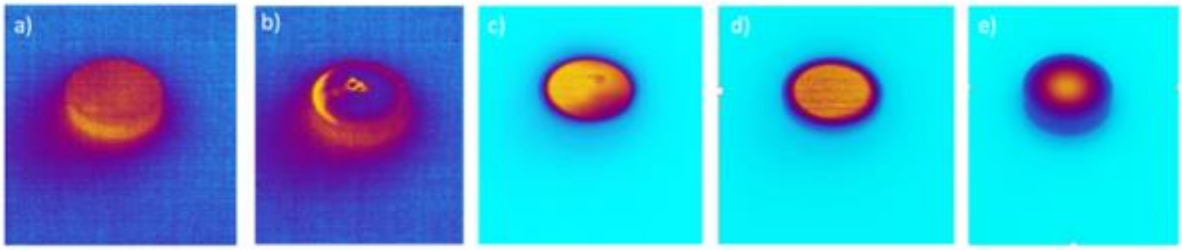


Figure 5: Thermal images of the cure at the following times: a) 0 seconds, b) 8 seconds, c) 10 seconds, d) 15 seconds, e) 2 minutes. The thermal imaging software auto-scales as the images are acquired for increased contrast.

To reduce the rate of the polymerization less photoinitiator and lower intensity lights were used as well as adding a neutral density filter to further drop the intensity. The photoinitiator concentration was reduced from 0.5 weight percent to 0.01 weight percent and the light intensity was reduced from 5 mW/cm^2 to 150 µW/cm^2. It was found that a distance of 20 cm from the lens to the light source was optimum for the most uniform cure. A light box was used to obtain a uniform cure throughout the lens. Figure 6 shows the optimum set up to obtain high quality polymer lenses.

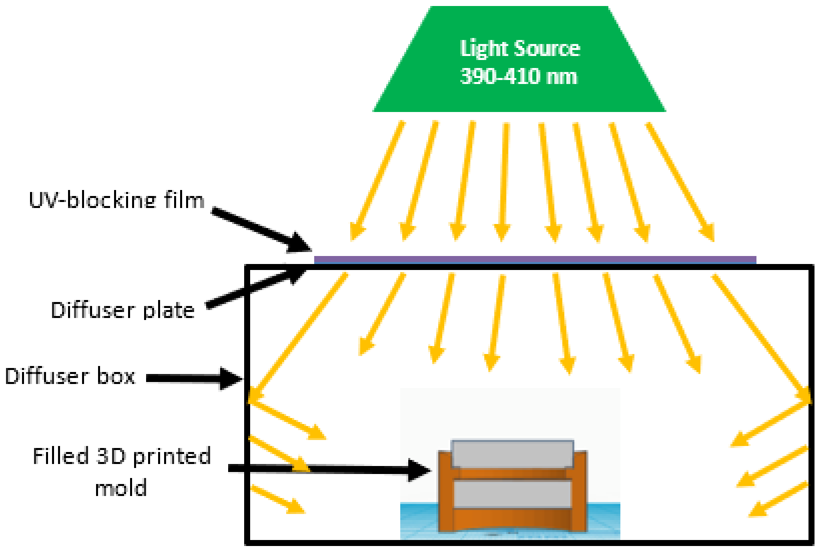


Figure 6: Cure schematic for lens fabrication.

Results:

Table 2 shows two different thiol/acrylate UV curable lens formulations that yielded optical quality glass in both crown and flint materials. These materials were molded using a flat custom 3D printed mold and cured in the method explained above. CPS 2 was chosen to be made in several different configurations due to its low wavefront error. Figures 7 and 8 show CPS 2 made in a flat configuration.

Table 2:

Polymer	Refractive Index	Abbe Number	Cure Type	Material Type
CPS 2	1.54	50	UV	Crown
CPS 13	1.56	34	UV	Flint

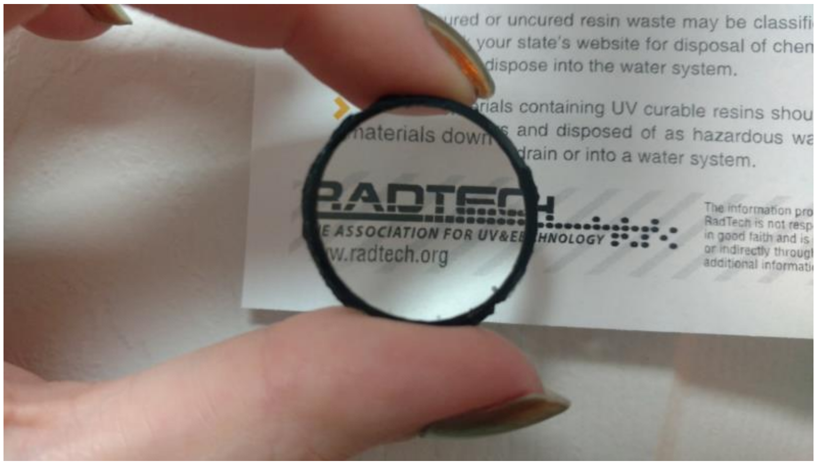
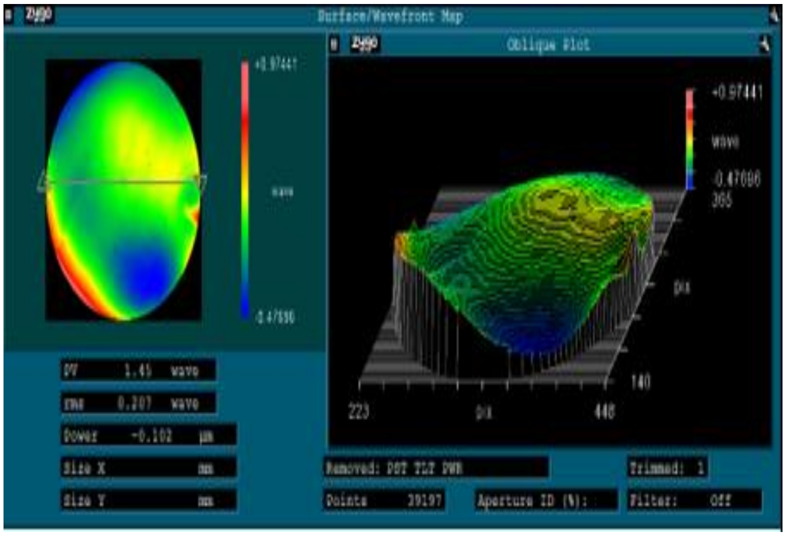


Figure 7: CPS 2 shown in a flat configuration. CPS 2 is a crown material and has a refractive index of 1.54 and an Abbe number of 50.

Figure 8: CPS 2 shown in a flat configuration. CPS 2 is a crown material and has a refractive index of 1.54 and an Abbe number of 50.

Using Zygo laser interferometry, the fabricated lenses were analyzed for their peak-to-valley height (PV), root-mean-square (RMS) value, and power. A wavefront map of the results can be seen in Figure 9. The PV value indicates how much the lens surface deviates from an ideal, perfectly smooth surface, and RMS is the average of PV values taken from a lens. A summary of the results for different lenses is given in Table 3.



PV 1.45 wave
rms 0.207 wave
Power -0.102 µm
Size X mm
Size Y mm
Removed: PST TLT PWR
Trimmed: 1
Points 39197
Aperture ID (%):
Filter: Off

Figure 9: Wavefront map of the flat lens prepared with CPS 2.

Table 3:

Material	**Configuration**	**PV (waves)**	**RMS (waves)**	**Power (µM)**
Glass Mold	*Flat*	*0.30*	*0.063*	*0.088*
CPS 2	Flat	1.45	0.207	-0.102
CPS 2	Convex	1.79	0.375	-0.151
CPS 2	Biconvex	4.72	0.974	0.151

As seen in Table 3 the CPS 2 has a PV value in the flat configuration of 1.45 compared to a glass mold of 0.3. A PV value less than 2 is considered substantial and a PV value less than 1 is considered good optical quality glass. The curing optimizations described in this work have led to the PV value of the polymer optics decreasing substantially and continued improvements are anticipated.

Conclusion:

Utilizing UV curable polymers to create optics has several advantages over traditional glass optics. The minutes needed to mold a polymer optic compared to the days needed to produce a commercial glass optic in conjunction with the low-cost set up of UV curing certainly makes it a desirable manufacturing process. While the optical quality of the polymer optics is quite good, additional progress is still needed to fabricate high quality optical polymers.