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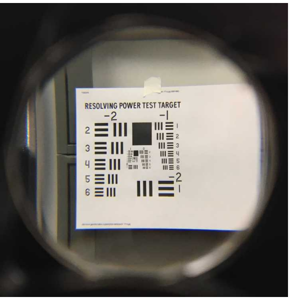

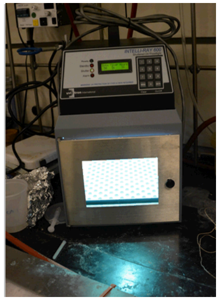

UV-Cured Polymer Optics

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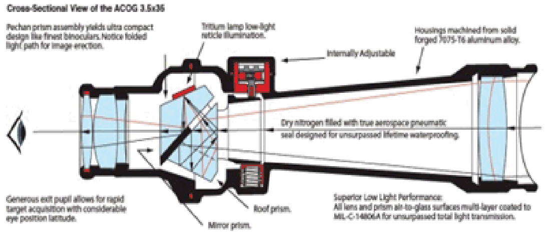
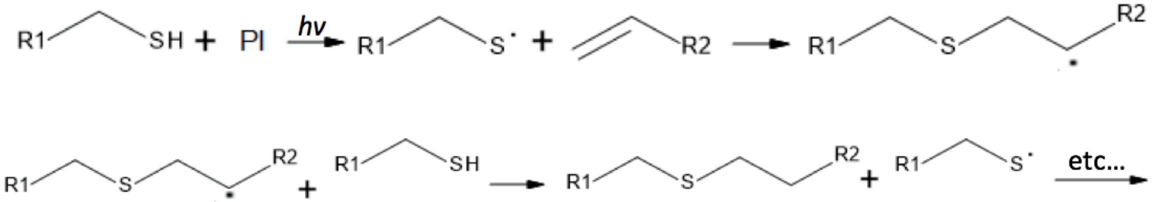
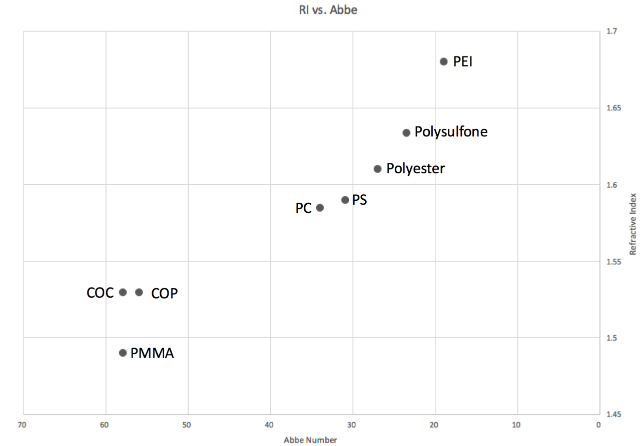
Project Overview



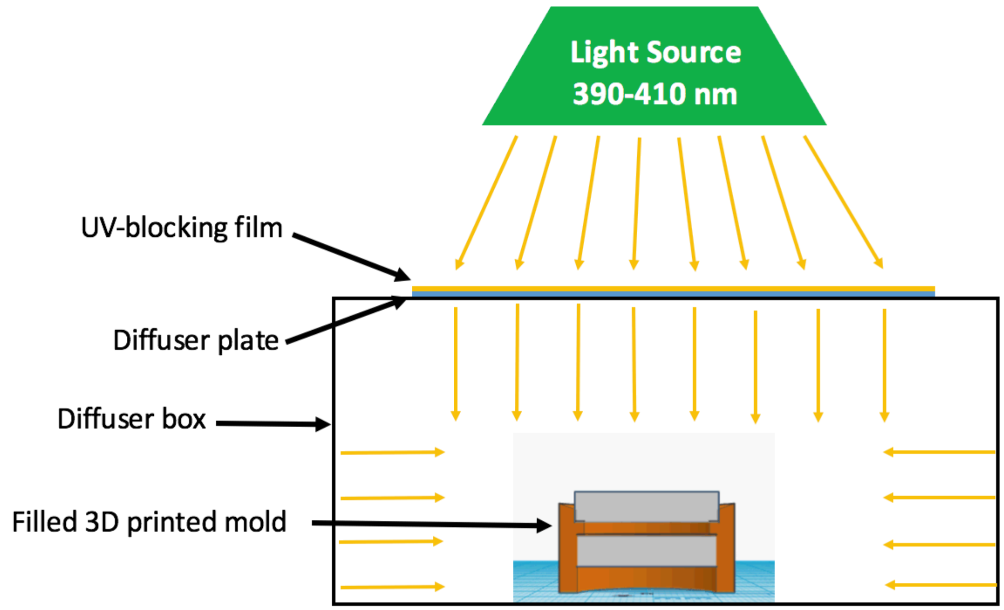
- By replacing glass optics we stand to reduce weight in DVOs
- Developing a mold replication-based system we could reduce production cost and increase production rate.
  - A modular mold-based system ideal for low-budget R&D labs/universities
- The production can be expanded to produce complex optics
  - Spherical/aspherical, singlet/doublet, inherent mechanical features built into optics
  - Can we avoid post-cure processing?
- Can we develop a low-cost material and mold system robust enough to meet Military Specs and tolerances?
- By combining the expertise in optical design and manufacturing of polymer lenses (SNL, NRL) with the expertise in photopolymerization and photopolymer development (CPS), the team is the prime candidate to develop photopolymer-based lenses for use in DVOs

Photopolymers



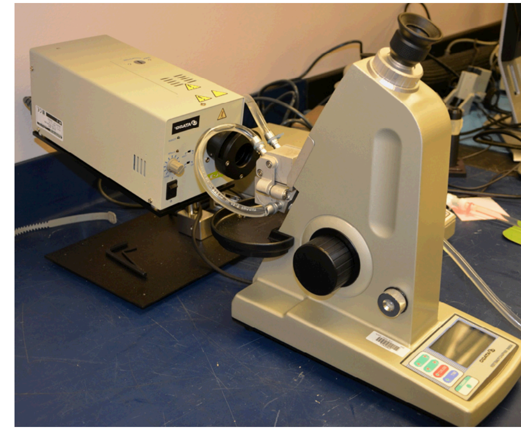


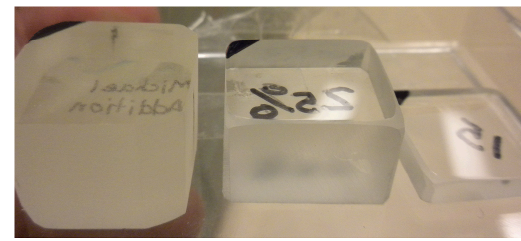
- Utilize reactive end-groups to polymerize/crosslink a network
  - Thiol-ene "Click Chemistry" Reaction
- One step reaction with minimal byproducts
- Tolerant to broad range of monomers/macromonomers
- Irreversible and high-yielding
  - Opposed to thermosets (molded optics
- Fast reaction time
  - Screen multiple monomers



Resin Development

- Preliminary screening for refractive index and Abbe
- Formulation optimization to tune properties
  - Photoinitiator, concentration of PI, resins and ratios, and crosslinkers
    - Retain amorphous quality (clarity)
  - Cure time, wavelength, source (intensity)
  - Post-cure bake
- CTE, polishing, toughness





Measured Refractive Indicies TPIV-023-024

Wavelength (nm)	Material # 1	15
450	1.5648	1.5601
485	1.5605	1.5567
589	1.5518	1.5478
651	1.5482	1.5445
680	1.5474	1.5435
Abbe Number	44.86178862	44.90163934
Designation	flint/crown	flint/crown
Material Description	CPS-MBI	CPS-MBI
Lot	1	Polished
Thin/Thick	thin	Thick

Measured Refractive Indicies

Wavelength (nm)	Material # 3	17
450	1.5402	1.5438
485	1.5387	1.5416
589	1.5317	1.5308
651	1.5285	1.528
680	1.526	1.5271
Abbe Number	52.12745098	39.02941176
Designation	crown	flint
Material Description	Thiolene 25	25%
Lot	1	Polished
Thin/Thick	thin	Thick

Measured Refractive Indicies

Wavelength (nm)	Material # 22	23
450	1.5388	1.539
485	1.535	1.5352
589	1.528	1.5278
651	1.5253	1.5256
680	1.5242	1.5247
Abbe Number	54.43298969	54.97916667
Designation	crown	crown
Material Description	High RI Resin 1-1	High RI Resin 1-2
Lot	3	3
Thin/Thick	thin	thin

Measured Refractive Indicies

Wavelength (nm)	Material # 2	13
450	1.6091	1.6056
485	1.6047	1.5991
589	1.5923	1.5875
651	1.5879	1.5833
680	1.5866	1.5816
Abbe Number	35.25595238	37.1835443
Designation	flint	flint
Material Description	CPS BPA	CPS BPA
Lot	1	Polished
Thin/Thick	thin	Thick

Measured Refractive Indicies

Wavelength (nm)	Material # 4	18	25	26	27
450	1.5372	1.5375	1.5368	1.5374	1.5375
485	1.5332	1.5323	1.5326	1.5338	1.5349
589	1.526	1.5246	1.526	1.5261	1.5264
651	1.5231	1.5223	1.523	1.5235	1.5235
680	1.5221	1.5214	1.522	1.5222	1.5227
Abbe Number	52.07920792	52.46	54.79166667	51.0776699	46.1754386
Designation	crown	crown	crown	crown	flint/crown
Material Description	Thiolene 15	15%	85/15-1	85/15-2	85/15-3
Lot	1	Polished	3	3	3
Thin/Thick	Thin	Thick	thin	thin	thin

Measured Refractive Indicies

Wavelength (nm)	Material # 24
450	1.5351
485	1.5314
589	1.5244
651	1.5214
680	1.5209
Abbe Number	52.44
Designation	crown
Material Description	High RI Resin 2
Lot	3
Thin/Thick	thin

Initial Library of Materials

Polymer	RI	Abbe
MBI	1.55	44.9
BPA	1.59	36
Thiolene 25	1.53	45
Thiolene 15	1.53	52
CPS7	1.51	53
Michael	1.55	46
High RI 1	1.53	54
High RI 2	1.52	52
2A	1.56	25

Preliminary Optical Design

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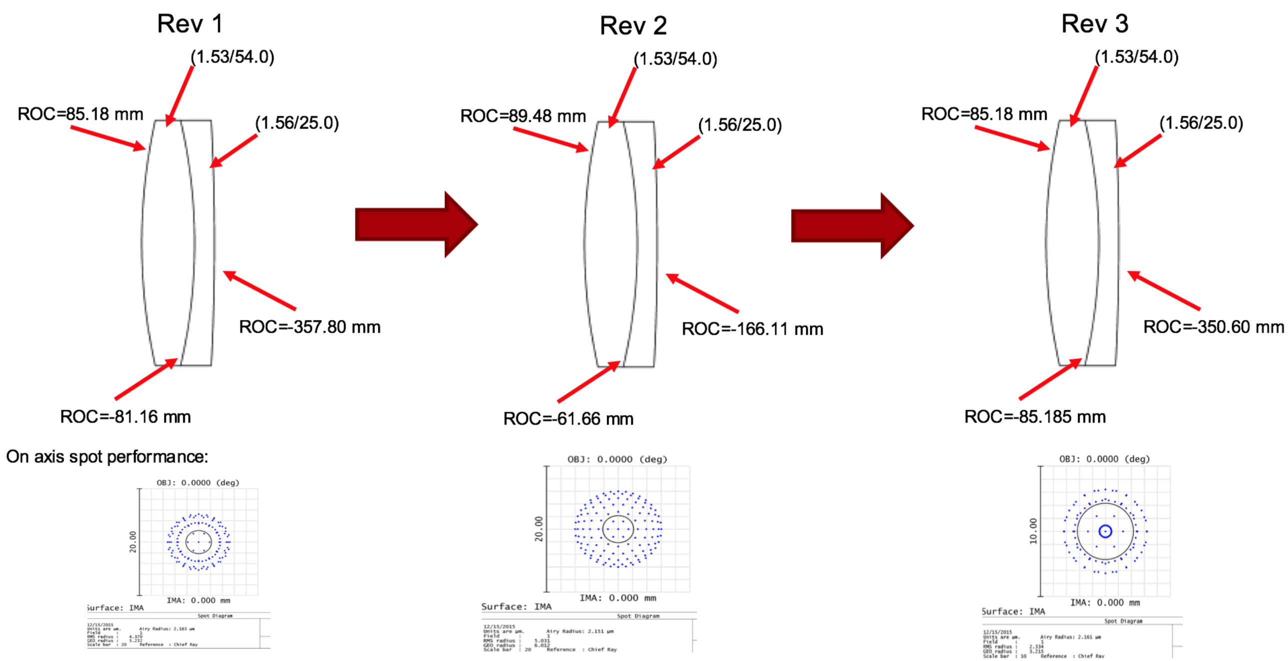
- Clarity, high transmission, low wavefront error, replication of mold surface
- Objective easiest starting point
- Doublet- need crown and flint
- Start with available materials
    - CPS continued to develop formulations

Polymer/Formulation	RI	Abbe
MBI	1.55	44.9
BPA	1.59	36
Thiolene 25	1.53	45
Thiolene 15	1.53	52
CPS7	1.51	53
Michael	1.55	46
*Crown → High RI 1	1.53	54
High RI 2	1.52	52
Flint → 2A	1.56	25



Zemax and a deconstructed ACOG were used to calculate prescriptions for new objective

*Since this is based on molded optical surfaces, we needed commercially available counterparts

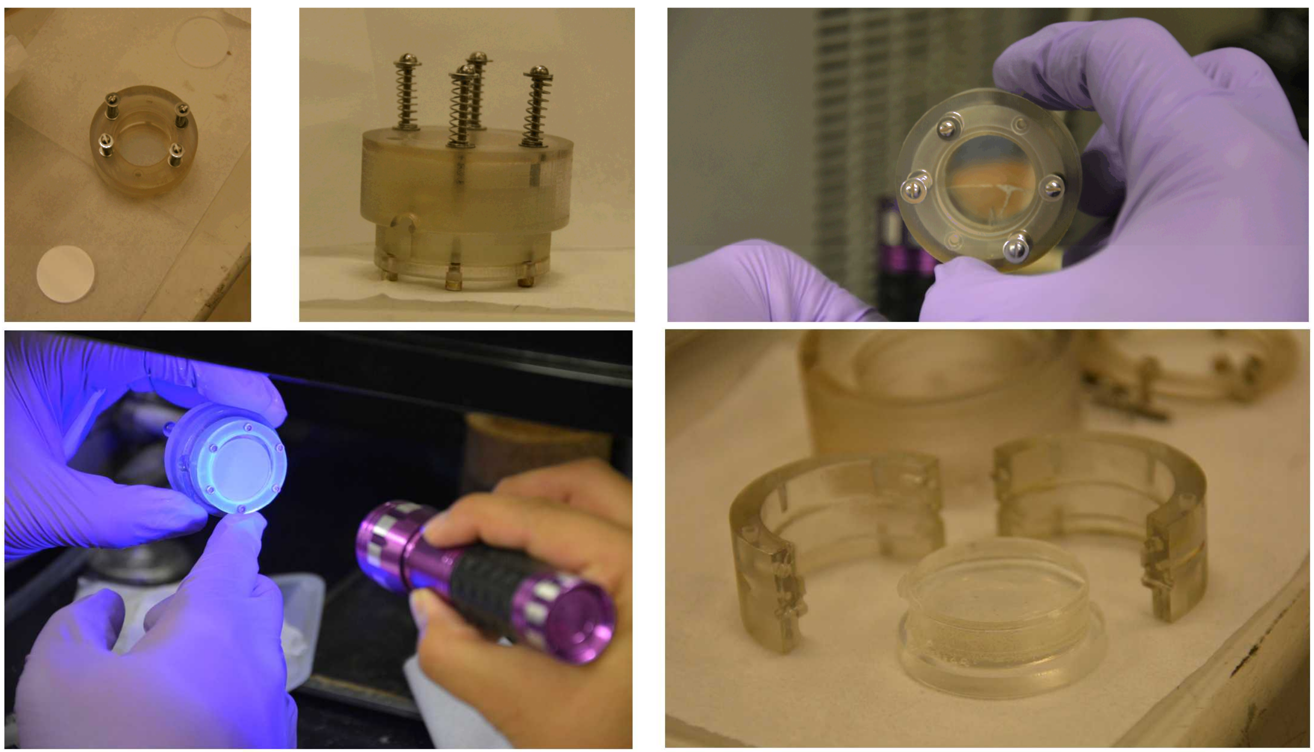
From paper to plastic...

(everything works until you actually try it out)

Simple Process

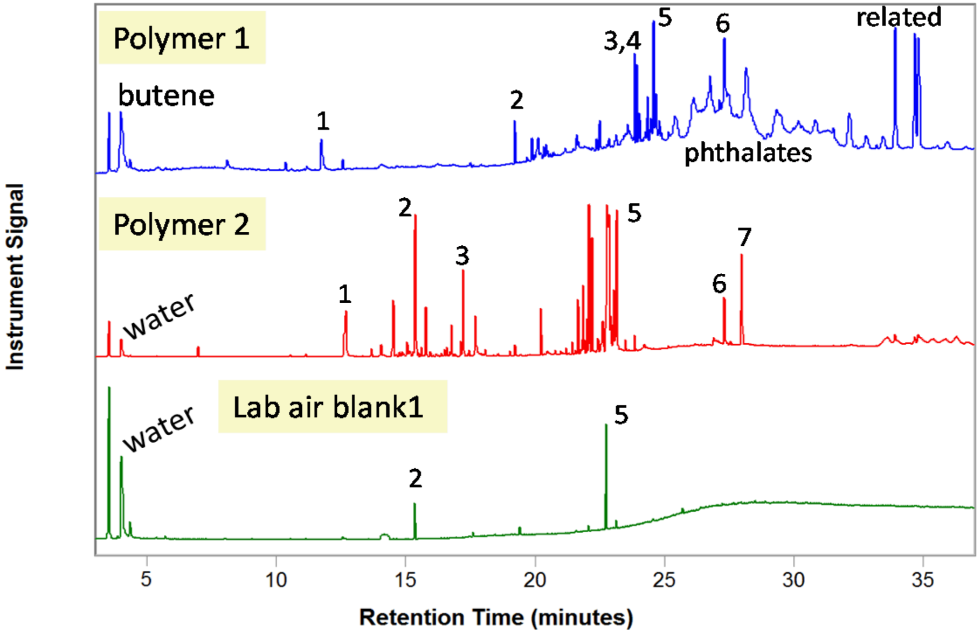
In UV-protected environment

- Assemble mold (commercial optics as molding surfaces ****fluorinate surfaces first!!!)
- Degas resin
- Expose to UV light
- Remove from mold



Delamination

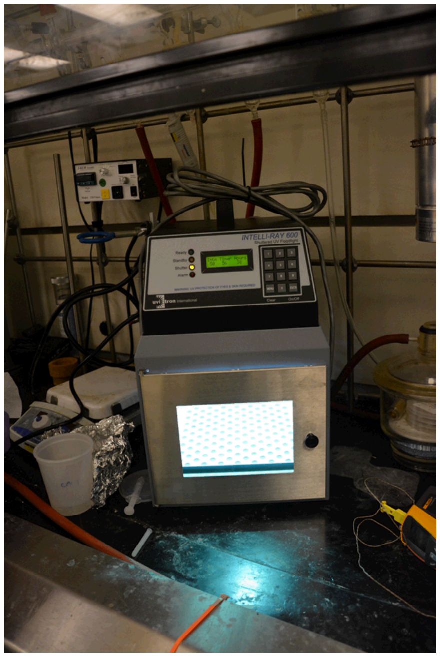
- Initial curing experiments resulted in very non-uniform surfaces – very good in certain areas but delaminated in other areas
  - Possible causes – temperature swing, stresses developing within the material, anisotropic curing.... Unexpected gas evolution???



Ex. Tetrachloroethylene boils at 87 °C

Label / Retention time	Best library match
1. 11.73	tetrachloroethylene
2. 19.22	phenol
3. 23.84	Butylated hydroxy toluene
4. 23.93	Bis-acrylamide (crosslinker)
5. 24.59	Chlorinated
6. 27.33	Irgacure 184 (photocure initiator)
1. 12.71	2-propenoic acid
2. 15.36	Camphene (similar to monomer)
3. 17.23	cymene
4. 20.22	Glycidyl acrylate
5. 23.16	Isobornyl acrylate (similar to monomer)
6. 27.32	Irgacure 184 (photocure initiator)
7. 28.01	Pentaerythritol triacrylate (crosslinker)

Curing Temperature Studies



Resin	Curing Oven Start Temp. (ºC)	Curing Oven Final Temp. (ºC)	Flashlight Start Temp. (ºC)	Flashlight Final Temp. (ºC)
CPS7	30	118	24	121
HR1	30	128	26	118
HR2	30	105	25	110

Band	Curing Oven (mJ/cm²)	Flashlight (mJ/cm2)
UVA	58.379	0
UVB	4.04	0
UVA2	39.851	7.644
UVV	64.891	18.684

-Even after a 2 second exposure with the low power flashlight, the temperature spiked to its high temperature, then slowly dropped

-Resin remained hot for minutes after curing finished

-Heat generated by exothermic curing reaction

Materials expand when heated... However, if the thermal energy is causing crosslinking to occur, opposing forces make this dimensional change difficult to predict... Can we control this?

LWIR Video of Reaction

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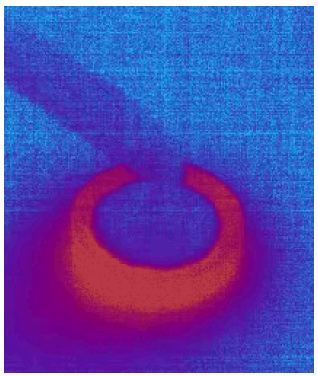
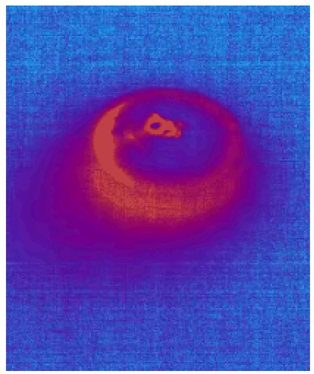
Does the heat evolve in a uniform manner?



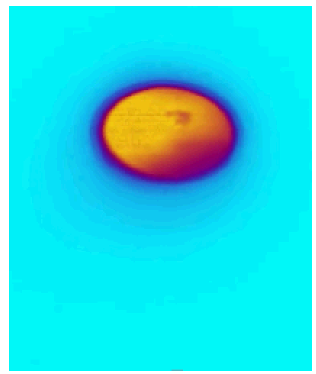
Thermal video of resin curing on concave lens, no secondary optics

6 sec



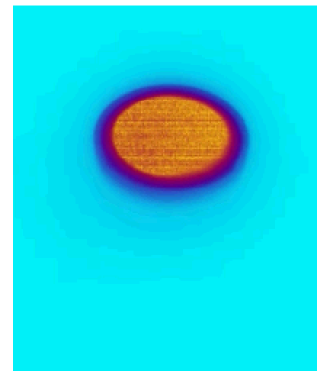
- Starts to cure from one side (light source was above and to the left)
- Air bubbles can be seen in resin

9 sec



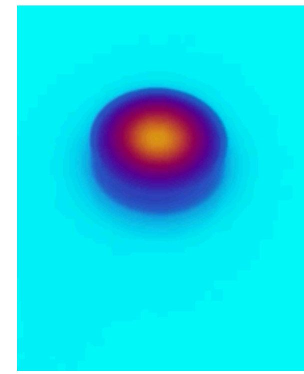
- Non-symmetrical temperature gradient.
- Air bubbles at different temperature

12 sec



Almost uniform temperature gradient on the surface. (Ideally we will want this)

45 sec



Symmetrical pattern but the radial gradient can be problematic to maintain the flatness or curvature mold. If this is repeatable, for a flat optics we will have to accommodate with the mold.

-1” concave optic as mold
-open environment cure

Mitigating Temperature Rise

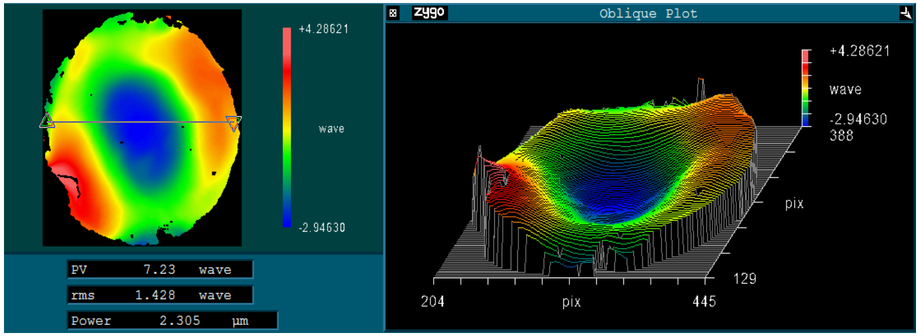
- Diffusers and ND filters at the light source or in line with the curing optic (incorporated into the mold)
- (For flat) UV flashlights on both top and bottom and resin exposed in intervals of 1 minute. *Addresses the fact that the source-side of the cured resin replicates the mold better
- (For curved element) UV LED source illuminated from one side.

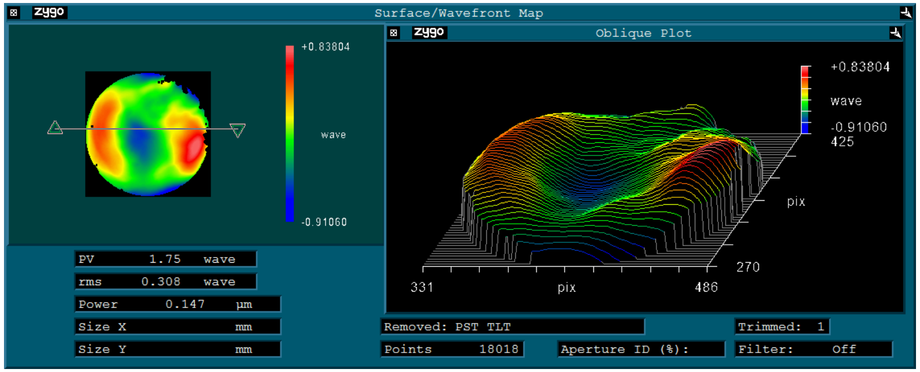
Result:

- Reaction of temperature was maintained around 32°C
- Initial diameter of optic 25.4 mm (PV=2.03 waves), edges trimmed to 24.8 mm (PV=1.75 waves/1.11 microns, 0.24 micron rms).

*Opposite surface separated from the resin, showed signs of delamination.

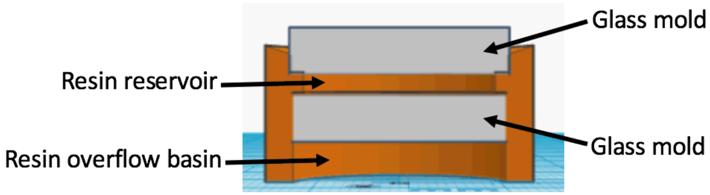
Flat – Original Process
No aberrations removed
PV = 7.23 waves



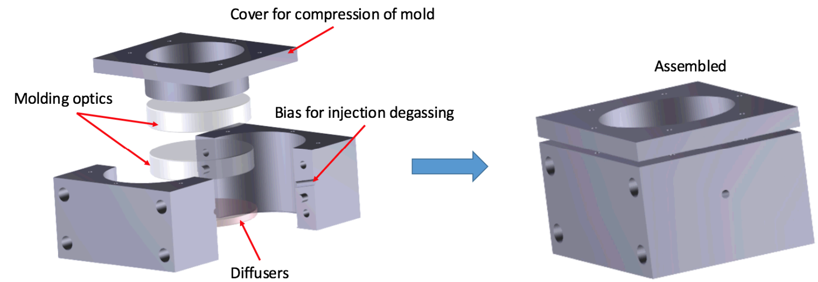


Flat - New process.
No aberration removed
PV = 1.75 waves

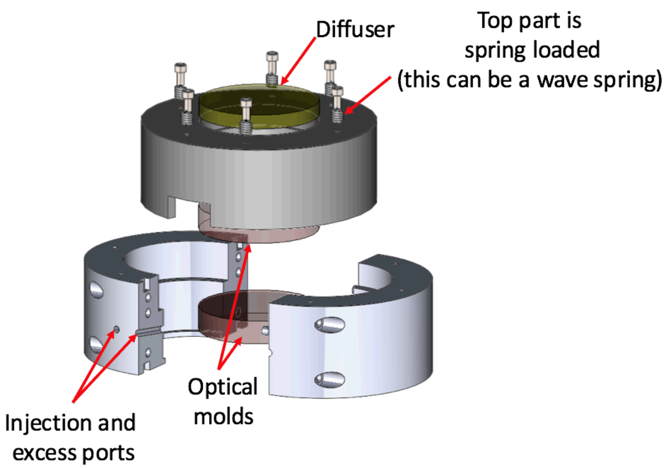
Mold Development



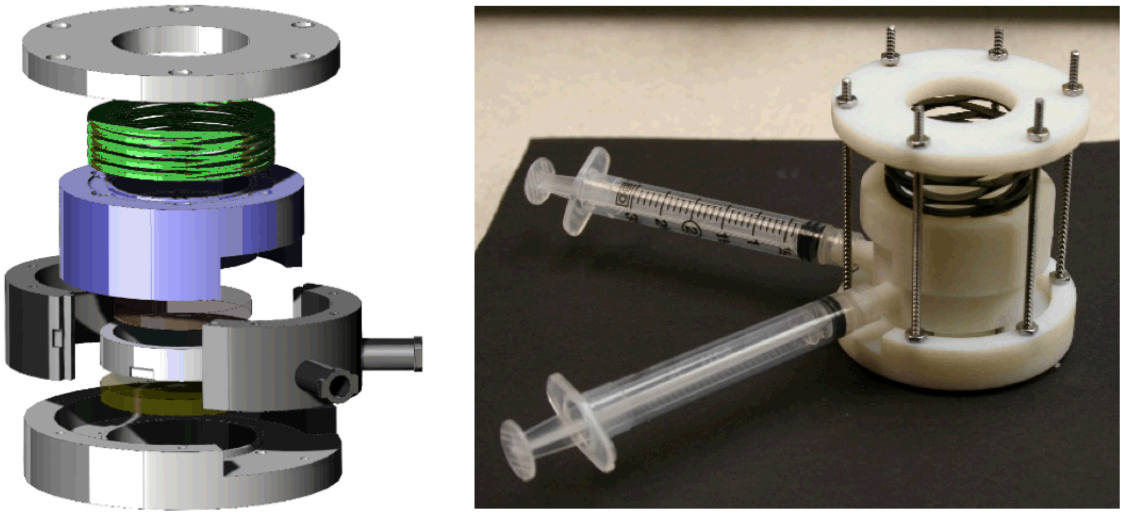
Surprisingly low wavefront error!
(one side only)



Diffusers to remove hazing, degassing port added



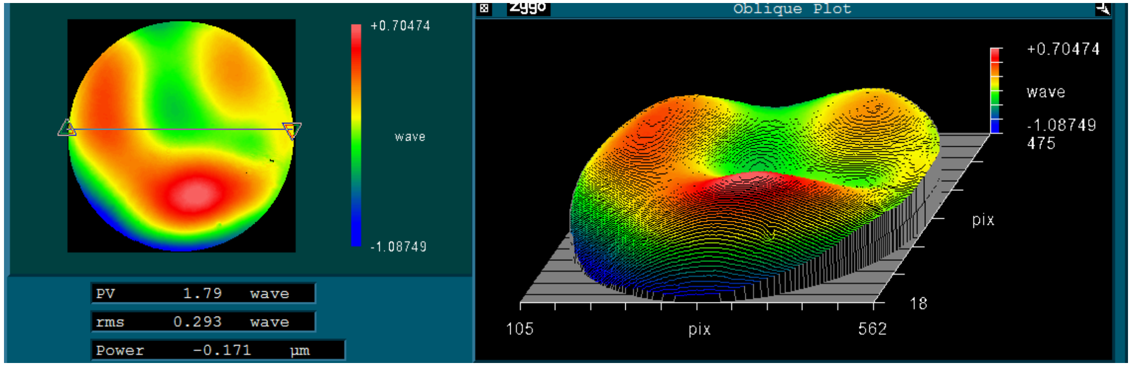
Springs to accommodate expansion and contraction



Wave spring for uniform compression, soft gasket to accommodate in-plane motion

Optimizing Curved Optics

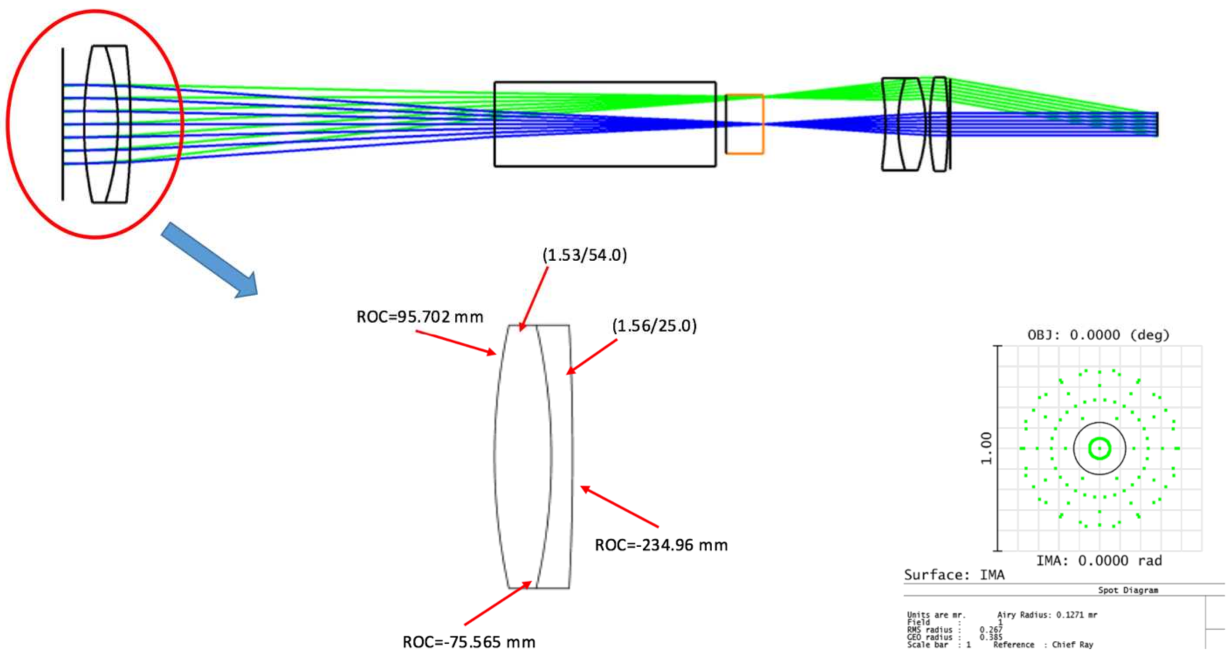
- High concentration of thiol and trifunctional acrylate ensures high degree of crosslinking
  - High refractive index:
    - RI = 1.54
  - High Abbe number:
    - Abbe = 50
  - Wavefront error (PV):
    - Lowest PV to date:
      - Flat configuration: 1.70 waves
      - Biconcave configuration: 4.72 waves



Curved lens. No aberration removed
PV = 1.79 waves (1.1 micron)

Old process				New Process			
Lens #	Aperture(mm)	ROC(mm)	PV(waves)	NP Lens #	Aperture(mm)	ROC(mm)	PV(waves)
22	13.05	54.805	14.75	AV5	13.70	51.39	2.13
38	12.67	53.23	2.96	AV6	13.82	50.84	4.93
42	13.69	57.51	5.51	AV7	13.75	51.27	3.13
78	13.68	56.38	5.38	AV8	13.75	51.56	1.79
89	13.7	55.45	7.44	--	--	--	--
Mold (lens)	13.71	-51.60	0.34	Mold(lens)	13.71	-51.60	0.34

Final Objective Design



3.75x magnifier (similar to ACOG but without reticle)

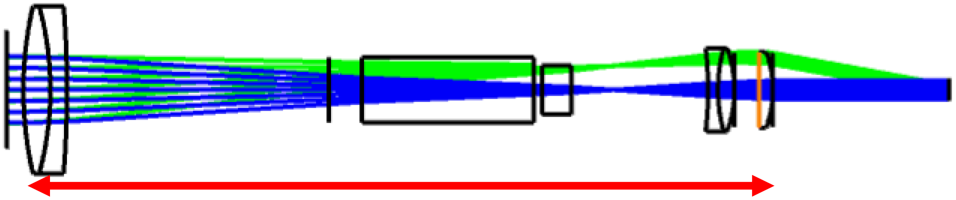
Utilizes original prism erector of an ACOG

Optimized for performance at 640nm

Custom Design

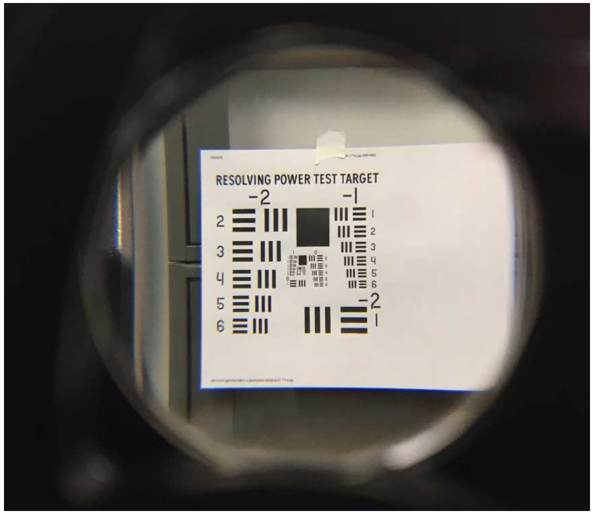
Sandia National Laboratories

- Magnification 3.75x
- FOV 5.5°
- COTS components for objective, prism erector and eyepiece lens
- Polymer resin lens as eyepiece
- Weight:
  - Singlet made out of N-BK7 ~4.34g
  - Singlet polymer ~1.95 g

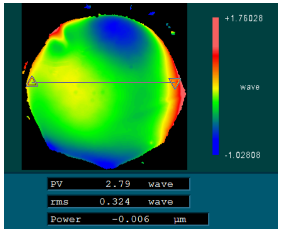


~167.0 mm (~6.5 in)

Using the polymer eyepiece, the center of the image is clear and in focus, but aberrations increase as we move off-axis. This is mostly due to the separation process of the polymer optics from the mold, as can be seen on the wavefront images on the right for full aperture and edges removed.

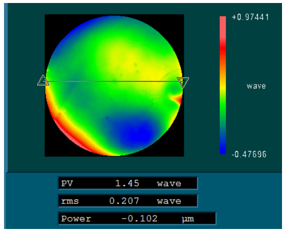


Full aperture



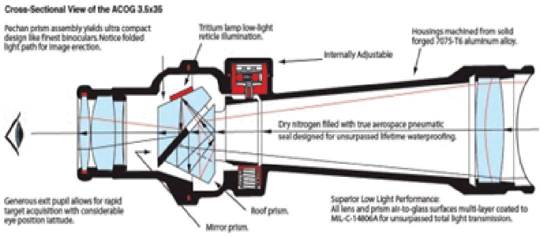
2.79 waves

Edges removed



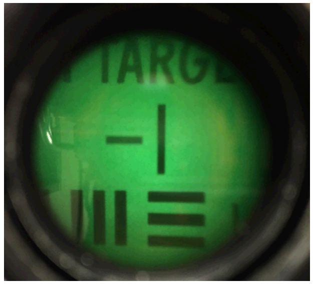
1.45 waves

Future Work



- Improve wavefront error
- Doublet studies
  - Use semi-cured materials/uv-curing cement/build one lens directly in contact with the second
- Updated optical design (reflect newer materials)
- System integration – housing, athermalization strategies
- Examine performance at longer wavelegths

- Polymer and resin development
- Incorporation of functionality into materials
  - GRIN lenses, anisotropic materials



Singlet polymer lens in front of NVG (NRL testing)

Singlet polymer lens (NRL testing)

Questions

vpinon@sandia.gov