Plastic Optics:

- Requirements
- Manufacturing
- Characterization

Light Prescriptions Innovators (LPI)
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## 1. Comparison Plastic/ Glass optics

<table>
<thead>
<tr>
<th>Property</th>
<th>Glass Optics</th>
<th>Plastic Optics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design freedom</strong></td>
<td>Mostly spherical, some aspheres</td>
<td>Any shape possible</td>
</tr>
<tr>
<td><strong>Fabrication methods</strong></td>
<td>Cut - grind - polish/ Molded lenses!</td>
<td>(Compression-) injection, embossing...</td>
</tr>
<tr>
<td><strong>Material Loss</strong></td>
<td>Large % is lost</td>
<td>No loss</td>
</tr>
<tr>
<td><strong>Polishing</strong></td>
<td>Very well developed</td>
<td>No polishing</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Medium - high</td>
<td>Low - medium</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>Typ. 2.6 (.5) g/ cm^3</td>
<td>Typ. 1.2 g/ cm^3</td>
</tr>
<tr>
<td><strong>Max operating temperature</strong></td>
<td>Tg: Typ 500ºC</td>
<td>Tg: 92/ 130ºC (PMMA/ PC)</td>
</tr>
<tr>
<td><strong>Aging/ UV resist</strong></td>
<td>Good</td>
<td>Yellowing</td>
</tr>
<tr>
<td><strong>Precision</strong></td>
<td>Very high</td>
<td>Low-medium (high?)</td>
</tr>
<tr>
<td><strong>Water absorption</strong></td>
<td>low</td>
<td>High for PMMA/ Medium for PC, low for COC</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td>Achromats</td>
<td>Integration of small features “at no cost” (mirolenses, integrating optics, diffusers, diffractive structures, information bits (DVD…))</td>
</tr>
</tbody>
</table>

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**Property of LPI Europe 2007**

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2. Typical applications

LED optics:

- Light Sources: LED “dome”
- Automotive: Signalling, illumination, interior
- Medical: Overhead Illumination, Medical instruments
- Indoor and outdoor general illumination
- Architecture: Floodlights, wallwashing, spots, ornamental lights
- Flash lights, Bicycle lights, head lamps…
- Backlighting: Mobil phones, PDA, Laptop, LCD screens
2. Typical applications

Non LED:

- Low quality imaging optics (disposable cameras, toys), developing to higher quality
- Automotive front and rear lighting
- Viewfinder prisms
- Light guides (fibers)
- Sensor optics
- Condenser lenses, illumination optics
- Solar concentrators: Lenses, Collimators, Light guides, Reflectors
- CD/DVD lenses and disks
3. Production/Toolmaking/Materials

Production is reproductive, as opposed to classical glass optics manufacturing.

Toolmaking
• High Speed milling
• 5-axis Diamond Turning Machine for Prototype and Mold Insert Fabrication
• Polishing
• Electro Forming
• Lithographic processes for microstructures

Typical Plastics
PMMA, PC, PS, COC, Silicones, many others
4. Parameters Plastic vs. Glass

<table>
<thead>
<tr>
<th>Property</th>
<th>Glass</th>
<th>Plastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>Transmission (180) 350 to 2000 nm</td>
<td>Transmission 350 to 1600 nm</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>Typical 1.52 (1.5..1.8)</td>
<td>PMMA 1.49, PC 1.59 , 1.53 COC</td>
</tr>
<tr>
<td>dn/ dT</td>
<td>&lt;-1 x 10^-6</td>
<td>-80 x 10^-6 (PMMA), -140 x 10^-6 (PC)</td>
</tr>
<tr>
<td>Abbe Nr</td>
<td>Typical 60, (25 .. 65)</td>
<td>PMMA 57, PC 34, COC 58</td>
</tr>
<tr>
<td>Absorption</td>
<td>Low</td>
<td>PMMA very low (cast material, higher for injected material), higher for PC</td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>Typical 6 x10^-6</td>
<td>Typical 80-140 x 10^-6</td>
</tr>
<tr>
<td>Birefringence</td>
<td>Low</td>
<td>Good for PMMA, poor for PC</td>
</tr>
</tbody>
</table>

For standard illumination, dispersion, dn/dT, and birefringence are normally not critical but for demanding optics they can be (i.e. projection lenses!)

Efficiency (surface roughness, absorption) is critical (LED flux is expensive)

For imaging optics plastics have to behave “glass-like”
4. Requirements plastic optics: Transmission

Typical available test data: for 2-4 mm thick probes

No distinction between Fresnell losses (about 4% at each surface) and absorption

Thick probes (as path length of light in the material) have to be measured and Fresnel reflections have to be carefully subtracted.

Target values for absorption losses:

<2% /10 mm for LED collimators

<2% / 30 mm for thick lenses

<2% / 200 mm for Backlighting units, Light guides
4. Requirements plastic optics: Dispersion

Important for:

Imaging/Projection lenses

Solar concentrators (Fresnel lenses)
4. Requirements plastic optics: Refractive Index

Higher Index Beneficial

- TIR optics
- Light guides

Higher \( n \) \implies\ higher acceptance angle
4. Surface Geometries

<table>
<thead>
<tr>
<th>Surface Shapes</th>
<th>Free parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>0</td>
</tr>
<tr>
<td>Rotational (Cylindrical) Spherical</td>
<td>1</td>
</tr>
<tr>
<td>Rotational (Cylindrical) Conic</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(hyperbolic, ellipsoidal, parabolic)</td>
</tr>
<tr>
<td>Rotational (Cylindrical) Ashperical</td>
<td>N</td>
</tr>
<tr>
<td>Freeform</td>
<td>NxM</td>
</tr>
</tbody>
</table>

N/ N is the number of polynomial terms or NURBS control points

More free parameters => more “powerful” optical design

More free parameters => more complex design methods and fabrication
5. Form Factor and Roughness

Surface Profile

Deviation from CAD, $z$

“Nano roughness”
Scale: 1 nm .. 1 um.

“Micro roughness”
Scale: 1 um .. 1 mm

Efficiency loss

Ray deviation

nm
microns

coherent
incoherent

Ray deviation

“Nano roughness”
Scale: 1 nm .. 1 um.

“Micro roughness”
Scale: 1 um .. 1 mm
5. Form Factor and Roughness

Example:
σ: the r.m.s. roughness
n: the POE refractive index
With: wavelength = 550 nm, n = 1.5, alpha = 45 deg

1% Scattered Power <=>

σ < 4 nm for Internal Reflection (metallic or TIR)
σ < 16 nm for Refraction

“Metallic or TIR surfaces must comply with much higher surface quality than refractive surfaces”
5. Form Factor and Roughness

Reflection
\[ \delta \theta = 2 \delta \varepsilon \]

Refraction (exiting from lens).
\[ \delta \theta = \delta \varepsilon \cdot (n-1) \approx \frac{1}{2} \delta \varepsilon \]

TIR or inner metallic reflection
\[ \delta \theta = 2 \delta \varepsilon \cdot n \approx 3 \delta \varepsilon \]

**Example:** Max allowable beam deviation: \( \delta \theta = 0.1^\circ \)
Max allowable slope error:
- \( \delta \varepsilon = 0.033^\circ \) TIR Reflection
- \( \delta \varepsilon = 0.2^\circ \) Refraction

“Wavelength” \( L \) of surface deviation \( d \). For TIR reflection:
\[ d = \frac{L}{2} \delta \varepsilon \]
- \( L = 30 \text{mm} \Rightarrow d = 8.6 \text{ microns} \)
- \( L = 3 \text{ mm} \Rightarrow d = 0.86 \text{ microns} \)

“Metallic or TIR surfaces must comply with much lower slope errors than refractive surfaces”
5. Form Factor and Roughness

Injection Related problems

Delamination

Sinks Marks and Weld Lines

Burr
5. Form Factor and Roughness

Tooling related problems

Most important: Tool quality
DT grooves replicate into surface!
“Rainbow effect” due to DT grooves
6. Examples: Light guides

• Absorption
• Surface roughness (many reflections!)
• Typical back light unit: 3 mm thickness, tapering, 20 cm and more in size
6. Examples: Light guides

- Thin gaps between arms <100 microns
- Surface quality
- Surface flatness
- Lowest draft angles

LPI has developed a highly effective injection-molding of proprietary combiner manifold optics
6. Examples: TIR-R

TIR-R system (PMMA):
- Ultra high efficiency concentrator
- 82% for sunlight

Or as LED collimator:
- 86% Total Efficiency including Fresnel and collection losses!

Solar cell or LED chip
Secondary lens
TIR lens
6. Plastic optics examples: TIR-R

TIR-R system- produced by LPI:
- TIR lens with small vertex angles (up to 28°)
- Diamond turned tool
- Ultra small convex and concave tooth radii in molded lens:
  - Convex: 5 µm average
  - Concave: 14 µm average, Min: 5 µm

Smaller radii are possible with compression molding and hot embossing
6. Examples: Imaging Lens

- Large center thicknesses
- High accuracy
- Small edge thickness

Example: 16 cm diameter, 32 mm thickness (!), injection molded PMMA

Extreme Example, not for production
6. Examples: Photon Funnel

• Typical HB LED collimator
• Uses TIR of back surface
• Standard product, normally made from PMMA
• Relatively large plastic volume
6. Examples: Microlenses and microstructures

- 1 mm in diameter
- Arrays of injected lenslets with high NA
- Replicated mold made by gray value lithography

- DVD surface structure
- 200 nm feature size
6. Examples: RXI headlamp

• Free from surfaces (no symmetry)
• Folded optics
• Front and back surface work as mirrors (highest accuracy)
• Very compact optics (one of the most compact collimator geometries that exist)

Low beam RXI
27 x 60 x 16 mm³
6. Plastic optics examples: 3D RXI

Problems:
• Non uniform shrinkage
• “warpage” due to vertical profile
7. Metrology

• Optical testing (Hartmann)
• Laser Interferometry (3D surfaces for Imaging system), i.e. Zygo
• CMM (3D measurement points, Zeiss)
• Stylus Profilometer (2D scans, Zygo, Zeiss)
• While light Interferometry (3D, FRT, Stil, Zygo)
• Laser scanner (3D, LDI)

Testing of plastics optics can be very difficult because surfaces are often freeform, very steep, and of very low reflectivity.
8. Summary

Plastic optics offer almost complete freedom of shape.

Optical systems can have much fewer, more efficient, lighter and cheaper elements.

Shrinkage and tool quality/wear are the main obstacles in order to make high quality plastic optics.

Many optics shown in this presentation are protected by LPI patents or patent applications.