Advanced Optics
by
Aspherical Elements

Engelberg
7. March 2007

Rüdiger Hentschel
Actual Impacts on Optics

- Modern Optics faces new challenges e.g.
  - Analogue vs. digital data/image acquisition
  - Special products vs. high volumes manufacturing

- Increasing requirements from application e.g.
  - Shorter wavelength, higher resolution, increased transmission (microlithography)
  - Smaller, weight reduced, telecentric, zoom lenses instead of fixed lenses (digital photography)

Consequence: Impact on complete value added chain
- Spheres $\rightarrow$ Aspheres $\rightarrow$ Free form surface
- Impact on each process step (design, materials, processing, metrology, coating, assembly)
- Modification of existing technologies vs. development of new technologies

Economical solution?
Goal of the Day

• Show structure of optical modern technologies

• Short and compressed information on management level

• Basic understanding of technologies
  (tool: optical technology reference book)
Optical Technology Reference Book:

**Advanced Optics by Aspherical Elements**

Edited by: B. Braunecker, R. Hentschel, H.J. Tiziani
(to appear at SPIE June 2007)

Content:

- Whole workflow in a short and compressed form
- Information provided on management level
- Detailed technology descriptions by experts’ contributions
- Links for further readings
- Template structure allows to compare alternative methods

Contributions of almost 60 experts:

- J. Alkemper
- B. Dörband
- C. Gunkel
- J. Korth
- H. Pulker
- B. Szyszka
- S. Bauer
- A. Dubarrè
- M. Haag-Pichel
- D. Kura
- B. Reiss
- H. Tafelmeier
- K. Beckstette
- H. Ebbesmeier
- H. Hagedorn
- E. Langenbach
- D. Ristau
- U. Tippner
- A. Bell
- M. Eisner
- P. Hartmann
- A. Laschitsch
- S. Ritter
- W. Ulrich
- T. Bergs
- O. Fähnle
- B. Hladik
- R. Litschel
- U. Schallenberg
- R. Völkel
- M. Biber
- M. Falz
- C. Horneber
- H. Mann
- B. Schreder
- A. Wälti
- R. Börret
- H. Feldmann
- A. Jacobsen
- R. Mayer
- A. Schwarzhans
- K. Weible
- U. Brauneck
- M. Forrer
- N. Kaiser
- M. Meeder
- K. Seneschal-Merz
- A. Würsch
- B. Bresseler
- E. Fischer
- P. Karbe
- R. Müller
- L. Stauffer
- J. Zimmer
- H. Buchenauer
- S. Gold
- C. Klein
- U. Peuchert
- T. Sure

16.02.2007
page 4

Dr. Rüdiger Hentschel
Advantages of new development:
...In the current prototype, two free-shaped prisms provide performance equivalent to a conventional coaxial lens that has three to five lens elements, and can achieve theoretical resolutions of 250 line-pairs per millimeter at the center, and 200 line-pairs per millimeter at the periphery.
...light rays strike the surface of the image sensor at a perpendicular angle.
...

Summary

Olympus Corporation (President: Tsuyoshi Kikukawa) is pleased to announce the development of a new, Free-Shaped Prism Type Lens Unit for use in camera-equipped cellular telephones. A prototype camera module with a thickness of 8.5 millimeters has been produced using the new lens unit, and has been demonstrated to support 1.3-megapixel resolutions. It is the thinnest such unit yet developed, and is notable for its potential to meet the performance demands of image sensors with a resolution in excess of two megapixels. A fully functional camera module incorporating the new lens unit and an image sensor is scheduled to be available in the fall of 2004.
Value Added Chain for Aspherical Lenses

- Design
- Materials
- Processing
- Metrology
- Coating
- Assembly
Design Drivers

The reduction of the number of optical components is only one reason to insert aspheres into optical systems. Other important design drivers are

- to increase the imaging quality (resolution; distortion), which can’t be achieved by a pure spherical design. Example: Deep-UV-Lithography.

- to reduce the construction size. Example: Photographic zoom lenses.

- to save weight, since one asphere is perhaps lighter than several spherical components yielding the same optical performance. Example: IR-Optics at 1-5 µm and 8-12 µm, made of ‘heavy’ Germanium- or Silicon material.

- to improve the total light transmission by reducing the number of optical elements. Example: Fluorescence microscopes with high transmission demands in the blue and UV spectral range.

- to simplify the assembly process
## Status of Aspherisation

<table>
<thead>
<tr>
<th>Application fields</th>
<th>Advantages and drivers</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Large quantities</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Illuminations</td>
<td>Better imaging quality with one element; cost reduction</td>
<td>Production</td>
</tr>
<tr>
<td>Laser Collimator</td>
<td>Better imaging quality with one element; cost reduction; beam stability</td>
<td>Production</td>
</tr>
<tr>
<td>Photo Optics</td>
<td>Necessary for zoom systems; cost reduction; better imaging quality; smaller construction length</td>
<td>Production</td>
</tr>
<tr>
<td>Large Format Film Lenses</td>
<td>Necessary for zoom systems; cost reduction; better imaging quality; smaller construction length</td>
<td>Production</td>
</tr>
<tr>
<td><strong>Small quantities</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UV-Lithography</td>
<td>Better imaging quality; higher transmission at UV wavelengths</td>
<td>Production</td>
</tr>
<tr>
<td>Aerial Survey</td>
<td>Better correction of distortion and telecentricity; cost, weight and size reduction</td>
<td>in Preparation</td>
</tr>
<tr>
<td>Space Communication</td>
<td>Light weight; compact layout; radiation resistance</td>
<td>Prototype</td>
</tr>
<tr>
<td>Correction Plate for Mirror Telescope</td>
<td>dito; better imaging quality</td>
<td>in Study</td>
</tr>
</tbody>
</table>
Value Added Chain for Aspherical Lenses

- Design
- Materials
- Processing
- Metrology
- Coating
- Assembly
Material Classification

Figure 14: Abbe-Diagram of Optical Materials (Fluids, Polymers, Glasses, Crystals)
Optical Designers need additional Information

Optical designers need information beyond $n_d$ and $v_d$:

- partial dispersion values $P$
- transmission values $T$
- stress optical coefficients $K$ and birefringence
- Chemical resistance against water, acids, and bases
- Mechanical properties like hardness (Knoop HK) and Young’s modulus $E$
- Thermal parameters like the thermal expansion coefficient $\alpha$, thermal capacity $C_p$, thermal conductivity $\lambda$, heat resistance, and the thermal shift of optical properties

Sometimes it is convenient to use deduced coefficients which describe the Material/system in real situations:

- specific thermal stress $\varphi_s = \frac{\alpha \cdot E}{1 - \mu}$ for the maximal expected stress in glass for a spatial local temperature difference of 1 K
- The specific heat conductivity $\kappa = \frac{\lambda}{c_p \cdot \rho}$ describes the heat diffusion in materials
How to get an Overview on Material Properties

Example: nd-vd-PgF-Pct-diagram (courtesy H. Schnitzler, Leica Microsystems AG)

Spatial dispersion coefficients are required for apochromatic lenses
How to get an Overview on Material Properties
How to get an Overview on Material Properties

![Graph showing Knoop hardness (HK) vs. refractive index (nd) for Glasses, Crystals, and Polymers]

- Glasses
- Crystals
- Polymers

Knoop hardness (HK)
Refractive index (nd)
Drivers for Material Development

A few examples of material development drivers:

• **Overall drivers:**
  – Environmental requirements e. g. Pb-free glass types

• **Technology drivers:**
  – PGM (Precision Glass Moulding) requirements e. g. Low $T_g$ glass types

• **Application drivers:**
  – Design drivers e. g. high index optical ceramics
  – User driven requirements e. g. low weight of optical components
Value Added Chain for Aspherical Lenses

- Design
- Materials
- Processing
- Metrology
- Coating
- Assembly
Historical Approach

The idea of polishing aspherical lenses is very old – but considerable results are obtained only within the last 100 years.

---

**Figure 22: Historical progress in generating and polishing processes**
Functional Approach

There are 3 main processing technology lines:
# Overview on Processing Technologies

Overview specifications and characteristics of the different processes (typical values in production)

<table>
<thead>
<tr>
<th>Process</th>
<th>Batch size</th>
<th>Dia.</th>
<th>Shape deviation</th>
<th>Surface roughness</th>
<th>Advantages</th>
<th>Limits</th>
<th>Main cost driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding</td>
<td>$&lt; 10^4$</td>
<td>2 - 400</td>
<td>1000</td>
<td>50 - 1000</td>
<td>Fast generating process</td>
<td>Subsurface damage</td>
<td>size, accuracy</td>
</tr>
<tr>
<td>Diamond turning</td>
<td>$&lt; 10^3$</td>
<td>2 - 400</td>
<td>100</td>
<td>5 - 20</td>
<td>No subsurface damage, for IR sufficient roughness</td>
<td>Surface roughness</td>
<td>size, accuracy</td>
</tr>
<tr>
<td>Speed / pitch polishing</td>
<td>$&lt; 10^4$</td>
<td>10 - 300</td>
<td>300</td>
<td>0.2 - 0.5</td>
<td>Very low surface roughness, fast polishing process</td>
<td>Correction of local surface deviations</td>
<td>size</td>
</tr>
<tr>
<td>CCP</td>
<td>$&lt; 10^3$</td>
<td>5 – 8000</td>
<td>30</td>
<td>0.5</td>
<td>30 years experience</td>
<td>Tool wear, edge roll-off</td>
<td>size</td>
</tr>
<tr>
<td>MRF</td>
<td>$&lt; 10^3$</td>
<td>5 - 500</td>
<td>10</td>
<td>0.3</td>
<td>No edge roll-off, no tool wear, low damaged surface layer</td>
<td>Center artefact for r-φ tool path</td>
<td>size, fluid</td>
</tr>
<tr>
<td>Fluid Jet</td>
<td>$&lt; 10^3$</td>
<td>5 -240</td>
<td>30</td>
<td>0.5</td>
<td>No edge roll-off</td>
<td>Stability of footprint</td>
<td>size</td>
</tr>
<tr>
<td>IBF</td>
<td>$&lt; 10^3$</td>
<td>5</td>
<td>0.2</td>
<td></td>
<td>No edge roll-off</td>
<td>Low removal rate</td>
<td>vacuum</td>
</tr>
<tr>
<td>Precision glass moulding</td>
<td>$10^4$ to $&gt;10^6$</td>
<td>0.5 -35</td>
<td>1-5</td>
<td>2</td>
<td>High volume</td>
<td>Size, accuracy</td>
<td>Cycle time, accuracy</td>
</tr>
<tr>
<td>Injection moulding</td>
<td>$10^4$ to $&gt;10^6$</td>
<td>0.5 - 200</td>
<td>1 -10</td>
<td>5</td>
<td>High volume, complicated shapes possible</td>
<td>Birefringence, micro structures</td>
<td>accuracy</td>
</tr>
<tr>
<td>Injection/ hot embossing</td>
<td>$10^4$ to $&gt;10^6$</td>
<td>0.5 - 200</td>
<td>1-10</td>
<td>5</td>
<td>Low birefringence, optics including mounting</td>
<td>thickness</td>
<td>Cycle time, accuracy</td>
</tr>
</tbody>
</table>
Surface Structure for different Processing Technologies

Measured surface deformations for different manufacturing processes
Example: Beam Rider for Line Marking

Laser collimator with aspheric lens

Laser diode

Asphere

Laserspot at 100 m

Lens with surface deformation
(Amplitude +/- 300 nm; spatial frequency 4 mm)

Ideal lens

Courtesy Leica Geosystems
Value Added Chain for Aspherical Lenses
## Classification of Surface Topography

<table>
<thead>
<tr>
<th>Roughness</th>
<th>Waviness</th>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>(high spatial freqs)</td>
<td>(mid spatial freqs)</td>
<td>(low spatial freqs)</td>
</tr>
<tr>
<td>$\Lambda \leq 20\mu m$</td>
<td>$20\mu m \leq \Lambda \leq 1mm$</td>
<td>$\Lambda \geq 1mm$</td>
</tr>
</tbody>
</table>
# Measuring Principle and Resolution

<table>
<thead>
<tr>
<th>Method</th>
<th>Spatial Resol. / meas. Spatial Range</th>
<th>Height Resol. / Height Range</th>
<th>Roughness</th>
<th>Waviness</th>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interferometry</td>
<td>1µm-1000µm</td>
<td></td>
<td>0.01mm</td>
<td>0.1µm</td>
<td>1µm</td>
</tr>
<tr>
<td></td>
<td>0.2nm-200nm</td>
<td></td>
<td>1nm</td>
<td>10nm</td>
<td>100µm</td>
</tr>
<tr>
<td>Macroscopic</td>
<td>10µm-2nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fringe projection</td>
<td>10µm-1nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microscopic</td>
<td>1µm-30µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fringe Projection</td>
<td>0.1µm-10µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confocal</td>
<td>0.5µm-30µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Principle</td>
<td>10nm-10µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White light</td>
<td>0.7µm-5µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interferometry</td>
<td>1nm-10µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Styles</td>
<td>100nm-100µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instrument</td>
<td>0.5nm-10µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scattering</td>
<td>100µm-100µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(λ=633nm)</td>
<td>0.5nm-10µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AFM</td>
<td>5nm-100µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.05nm-10µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Spatial resolutions, the practical range of the field and the rms height resolution together with the practical height range of potential techniques used for the measurement of optical surfaces (λ = 633 nm).
Value Added Chain for Aspherical Lenses

- Design
- Materials
- Processing
- Metrology
- Coating
- Assembly
What is the difference of coating technologies (1)

<table>
<thead>
<tr>
<th>Generation</th>
<th>Transport</th>
<th>Condensation</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOAT</td>
<td>Coating material is heated resistively or by e-beam</td>
<td>Thermical transport to substrate through high vacuum (some 1/10 eV)</td>
<td>Film growth; polycrystalline structures by resistive heating</td>
</tr>
<tr>
<td>IAD</td>
<td>Coating material is heated resistively or by e-beam</td>
<td>Thermical transport to substrate through high vacuum and ion beam (some 1/10 eV)</td>
<td>Compressed film growth by bombardment with energetic ions accelerated by an ion gun (some 100 eV))</td>
</tr>
<tr>
<td>IP</td>
<td>Coating material is heated resistively or by e-beam and ionised by a plasma beam accelerated from a low-voltage high-current electron source (working gas Ar und reaction gas e. g. O₂)</td>
<td>Coating material is accelerated by 2 effects: 1) Impact of ions 2) e-ionisation and acceleration</td>
<td>Film growth in a reactive gaseous environment and bombardment by energetic ions accelerated from ionised vapour source; polycrystalline structures by plasma</td>
</tr>
</tbody>
</table>
What is the difference of coating technologies (2)

**IAD** (ion-assisted deposition) courtesy of ….

**IP** (ion plating) courtesy of ….

---

16.02.2007  
Dr. Rüdiger Hentschel
What is the difference of coating technologies (3)

<table>
<thead>
<tr>
<th></th>
<th>Generation</th>
<th>Transport</th>
<th>Condensation</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>APS</td>
<td>Coating material is heated resistively or by e-beam</td>
<td>Thermical transport to substrate through a low-pressure plasma environment (some 1/10 eV)</td>
<td>Film growth in a reactive gaseous environment and concurrent bombardment with energetic ions accelerated from an Advanced Plasma Source</td>
<td>Dense, shift-free coatings with suburb layer qualities for optical and functional coatings</td>
</tr>
</tbody>
</table>
What is the difference of coating technologies (4)

**APS** (advanced plasma source)
courtesy of ....
In general Aspherical Lenses require no specific Coating Technologies

- Coating technologies got a big impact by telecom business
- Optical elements typically require an AR-coating (simple single layer MgF2 or 4-layer broadband coating)
- Coating technologies are not specific for aspherical lenses
Value Added Chain for Aspherical Lenses

- Design
- Materials
- Processing
- Metrology
- Coating
- Assembly
Assembly process and compensators

1st step: stochastical assembly

- Consumer Optics with **spherical** lenses
- High-end objectives with **spherical** lenses
- High-end objectives with **aspherical** lenses

2nd step: deterministic optimization

- Focus (1 compensator)
- + Focal Length (2 compensators)
- + Aberrations (>4 compensators)
- All parameters (N compensators)
Active Compensation (Micro-Optics)

Figure 46: Active compensating avoids the pile up of residual positioning tolerances
Active Compensation (Micro-Optics)

Courtesy Leica Geosystems
## Component Tolerances

<table>
<thead>
<tr>
<th>Component tolerances</th>
<th>Consumer Optics (spherical lenses)</th>
<th>HQ-Optics (spherical lenses)</th>
<th>HQ-Optics (aspherical lenses)</th>
<th>MicroOptics for photonics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive index</td>
<td>&lt; 10^{-4}</td>
<td>&lt; 10^{-5}</td>
<td>&lt; 10^{-5}</td>
<td>&lt; 10^{-4}</td>
</tr>
<tr>
<td>Abbe-number</td>
<td>&lt; 0.8%</td>
<td>&lt; 0.1%</td>
<td>&lt; 0.1%</td>
<td>&lt; 0.8%</td>
</tr>
<tr>
<td>Melt data</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Radius-deviation</td>
<td>&lt; 2\lambda</td>
<td>&lt; 0.2\lambda</td>
<td>0.2\lambda...2\lambda</td>
<td>&lt; 2\lambda</td>
</tr>
<tr>
<td>Surface form error</td>
<td>&lt; \lambda/5 rms</td>
<td>&lt; \lambda/20 rms</td>
<td>&lt; \lambda/20 rms</td>
<td>&lt; \lambda/5 rms</td>
</tr>
<tr>
<td>Centre thickness accuracy</td>
<td>± 40 (\mu)m</td>
<td>± 20 (\mu)m</td>
<td>± 20 (\mu)m</td>
<td>± 60 (\mu)m</td>
</tr>
<tr>
<td>Surface Roughness</td>
<td>&lt; 10 Å rms</td>
<td>&lt; 5 Å rms</td>
<td>&lt; 5 Å rms</td>
<td>&lt; 5 Å rms</td>
</tr>
<tr>
<td>Lens wedge error</td>
<td>&lt; ± 5 arcmin</td>
<td>&lt; ± 20 arcsec</td>
<td>&lt; ± 10 arcsec (?)</td>
<td>&lt; ±1 arcmin</td>
</tr>
</tbody>
</table>
## Assembly Tolerances

<table>
<thead>
<tr>
<th>Assembly tolerances</th>
<th>Consumer Optics (spherical lenses)</th>
<th>HQ-Optics (spherical lenses)</th>
<th>HQ-Optics (aspheric. lenses)</th>
<th>MicroOptics for photonics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single lens</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tilt error $\Delta \alpha$</td>
<td>$&lt; \pm 5 \text{ arcmin}$</td>
<td>$&lt; \pm 30 \text{ arcsec}$</td>
<td>$&lt; \pm 10 \text{ arcsec}$</td>
<td>$&lt; \pm 30 \text{ arcsec}$</td>
</tr>
<tr>
<td>Lateral decenter $\Delta r$</td>
<td>$&lt; \pm 50 \text{ \mu m}$</td>
<td>$&lt; \pm 10 \text{ \mu m}$</td>
<td>$\pm 10 \text{ \mu m}$</td>
<td>$&lt; \pm 1 \text{ \mu m}$</td>
</tr>
<tr>
<td>Axial displacement $\Delta z$</td>
<td>$&lt; \pm 50 \text{ \mu m}$</td>
<td>$&lt; \pm 10 \text{ \mu m}$</td>
<td>$\pm 10 \text{ \mu m}$</td>
<td>$&lt; \pm 1 \text{ \mu m}$</td>
</tr>
<tr>
<td><strong>Lens group</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tilt error $\Delta \alpha$</td>
<td>$&lt; \pm 30 \text{ arcsec}$</td>
<td>$&lt; \pm 30 \text{ arcsec}$</td>
<td>$&lt; \pm 10 \text{ arcsec}$</td>
<td>$&lt; \pm 30 \text{ arcsec}$</td>
</tr>
<tr>
<td>Lateral decenter $\Delta r$</td>
<td>$&lt; \pm 50 \text{ \mu m}$</td>
<td>$&lt; \pm 2 \text{ \mu m}$</td>
<td>$\pm 10 \text{ \mu m}$</td>
<td>$&lt; \pm 1 \text{ \mu m}$</td>
</tr>
<tr>
<td>Axial displacement $\Delta z$</td>
<td>$&lt; \pm 50 \text{ \mu m}$</td>
<td>$&lt; \pm 1 \text{ \mu m}$</td>
<td>$\pm 10 \text{ \mu m}$</td>
<td>$&lt; \pm 1 \text{ \mu m}$</td>
</tr>
<tr>
<td><strong>Compensators</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral position accuracy</td>
<td>NA</td>
<td>$\pm 0,2 \text{ \mu m}$</td>
<td>$\pm 0,2 \text{ \mu m}$</td>
<td>NA</td>
</tr>
<tr>
<td>Axial positioning accuracy</td>
<td>NA</td>
<td>$\pm 0,2 \text{ \mu m}$</td>
<td>$\pm 1 \text{ \mu m}$</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Operating temperature</strong></td>
<td>$0\degree \text{C}/+40\degree \text{C}$</td>
<td>$23\degree \text{C}\pm1\degree \text{C}$ or $-10\degree \text{C}/50\degree \text{C}$</td>
<td>$-10\degree \text{C}/+40\degree \text{C}$</td>
<td></td>
</tr>
</tbody>
</table>
Future Trends I

- Looking into the Abbe diagram, there are trends to extend the different material regions.

- Efforts are undertaken to generate glasses within the crystal nd-vd-area.

- Optoceramics will try to offer optical positions in the crystal field at lower costs.

- The economical fabrication of aspheres for high and medium quality, also in future, will be the main technology driver.

- The classical fabrication process of generating and polishing will be used for batch sizes smaller than $10^4$. 
Future Trends II

- The general trend will be to use the computer power for simulation the process within the machine
- Integration of processing and metrology
- Closed loop systems with wave front sensors adjust the flexible mirror surface to compensate the measured wave front aberrations
- Less expensive computer generated holograms (CGH)
- Hybrid techniques gain on importance
- Improvement on assembly technologies
  - Clueing and cementing materials
  - Micro-optics assembly by monolithic technologies will come up
- Cost reduction for aspherical elements down to 20 to 40% of actual manufacturing costs