High-resolution lenses for expert digital cameras: requirements for design and manufacturing

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The Nyquist-frequency of sensors in expert digital cameras achieve up to 125lp/mm at the time of this paper, mid-2018. Only lenses conceived and executed at very high standards are able to fully exploit their inherent potential. Such lenses require a complex optical design, very stringent production tolerances and immensely capable metrology through every stage of production.

1 Market overview

The resolution of modern digital cameras increases steadily. As the sensor size stays mostly unchanged, the pixel size decreases. Current state of the art being a resolution of 40 to 50 MPix at full-frame cameras (24·36 mm²) leads to a pixel size of slightly more than 4µm.

Most available lenses – many of them designed to meet much less demanding requirements - do not deliver satisfying or adequate optical resolution for these cameras, which is why there is a strong need for high-resolution lenses.

2 Limiting resolution: Sensor and lens

The limiting resolution at 4µm pixel size is defined by the Nyquist-frequency:

$$f_{Nyquist} = \frac{1}{2 \cdot 4\ \mu m} = 125\ lp/mm$$

For this reason the MTF of high-resolution lenses should also give 125lp/mm at good contrast of 50%.

3 Optical design

In the following we compare two purposely designed lenses: one represents an average performance the other a high-resolution model.

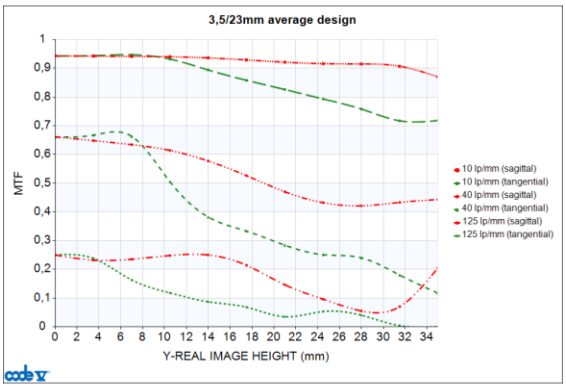

Fig. 1 *An average design: MTF for 10, 40 and 125 lp/mm.*

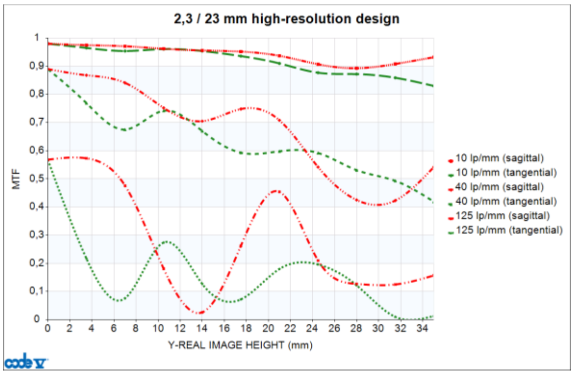

Fig. 2 *High-resolution design: MTF for 10, 40 and 125 lp/mm.*

Both designs have the same focal length of 23mm. The high-resolution design consists of 16 elements including multiple aspherics, whereas the average performance design has only 12 elements and is fully spherical. The complexity of the high-resolution design is significantly higher. In return we achieve a much higher optical performance.

4 Image simulation

A test chart showing a line pattern with decreasing line width is imaged through both virtual lenses by using raytracing.

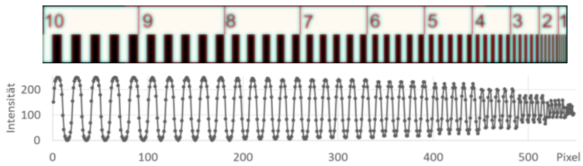

Fig. 3 *Contrast of an average performance design*

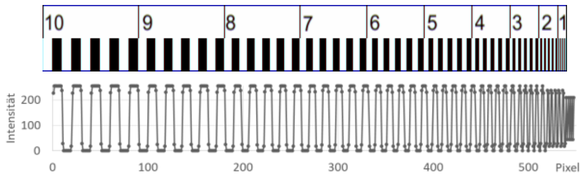

Fig. 4 *Contrast of the high-resolution design*

DGaO Proceedings 2018 – http://www.dgao-proceedings.de – ISSN: 1614-8436 – urn:nbn:de:0287-2018-B016-8

submitted: 27.Jul.2018 published: 03.Aug.2018

The numbers in fig. 3 and 4 are in units of the pixels width (4µm). '1' therefore means 125 lp/mm.

5 Manufacturing tolerances

Standard manufacturing tolerances are summarized in the following table.

Tolerance	Tolerance value
Refractive index n	0.0003 (Step 2 quality)
Abbe number v	0.003 (Step 2 quality)
Surface form error	3 fringes
Irregularities	1 fringe
Surface position (axial)	0.025 mm
Surface position (radial)	0.025 mm
Surface tilt	1 arcmin

6 Yield using stand tolerances

When the manufacturing procedure is simulated, the following yield can be achieved. Performance is deemed acceptable if the MTF decreases by not more than 10%.

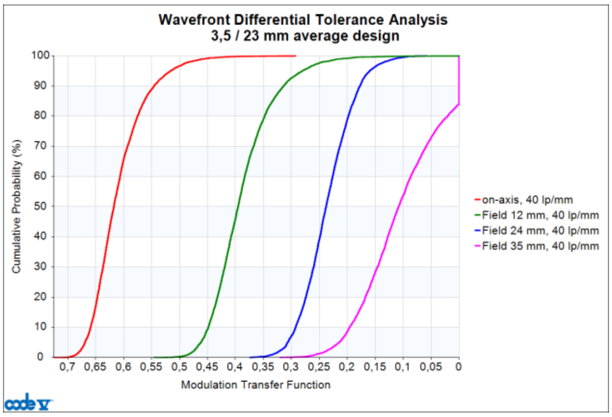

Fig. 5 *An average performance design: almost 90% of batch achieves at least 56% contrast at 40 lp/mm.*

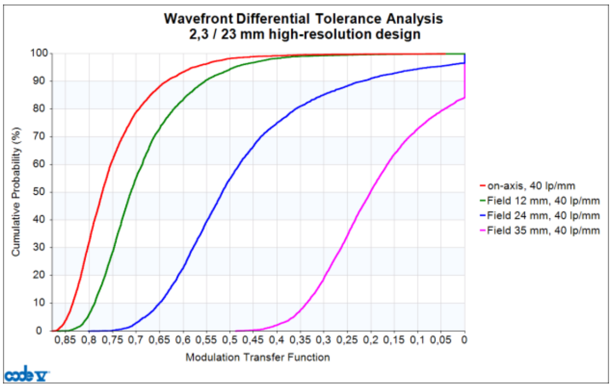

Fig. 6 *High-resolution design: 60% of the batch achieves at least 75% contrast at 40 lp/mm.*

At 40 lp/mm the yield for the average performance lens is good, for the high-performance lens it might just be acceptable. However at 125 lp/mm the yield is insufficient.

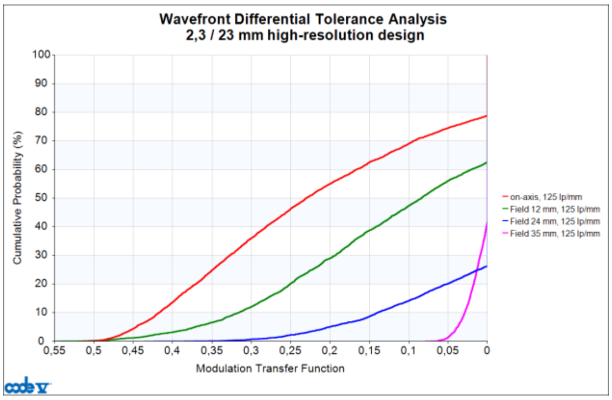

Fig. 7 *High-resolution design: only 15% of the batch achieves at least 40% contrast at 125 lp/mm.*

7 Yield using very tight tolerances

If the glass tolerances are reduced to Step 1 quality, surface position tolerances to 10 µm and tilt to 0.5 arcmin an acceptable yield is achieved.

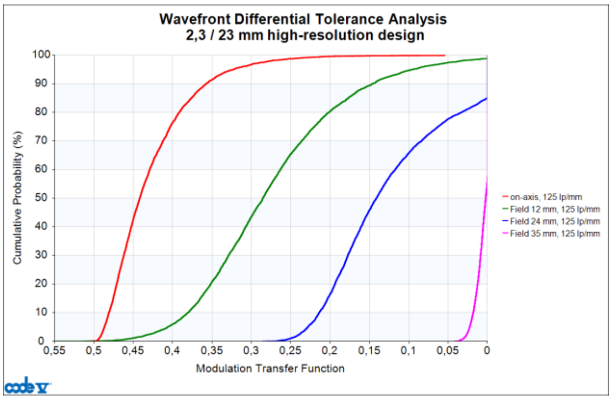

Fig. 8 *High-resolution design: 60% of the batch achieves at least 40% contrast at 125 lp/mm.*

8 Summary

Lenses of average performance currently available in general achieve around 40 lp/mm and can be manufactured with reasonable effort.

High-resolution lenses require not only innovative design but extremely tight material and manufacturing tolerances that lead to high production costs or additional features integrated in the lens to ameliorate yield. The latter requires not only more sophisticated metrology but also highly-trained and experienced assembly operators.

The perfect intersection and execution of ingenious optical design, thorough optimization, production planning as well as devoted adherence to tight production tolerances and assembly discipline enable a significant step forward in lens performance that promises to fully enable the potential in state-of-the-art expert digital cameras and sensors.

DGaO Proceedings 2018 – *http://www.dgao-proceedings.de* – ISSN: 1614-8436 – urn:nbn:de:0287-2018-B016-8

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