An Eight-Reflection Telephoto Lens

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Montage program design goals

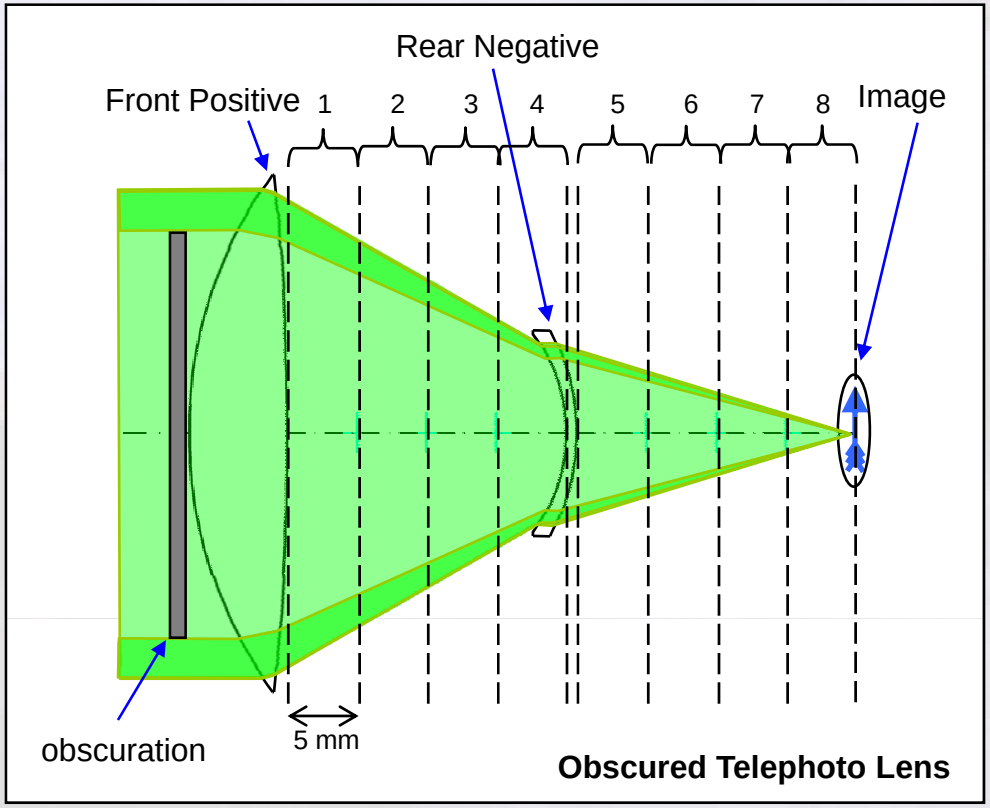
- **5 mm thickness (1st surface to sensor)**
- **0.1 (5.7⁰) radian field of view**
- **0.1 mrad resolution**
- **1000 x 700 pixel image**
- **Color imaging**
- **35 mm diameter effective aperture**

Specification flowdown

- Image field = 1000 x 700 pixels
  Choose Omnivision CMOS color sensor w/ 3.18 µm pixels
  → **Image field diameter = 3.90 mm**

- Optical Invariant: image height = tan (semi-FOV)*EFL
  (eg. h = 1.59, 0.1 rad FOV → **EFL ≈ 32 mm**) **…in 5mm track?**

Solution Concept: Obscured, Folded Telephoto Lens



Eight-Reflection Lens Design

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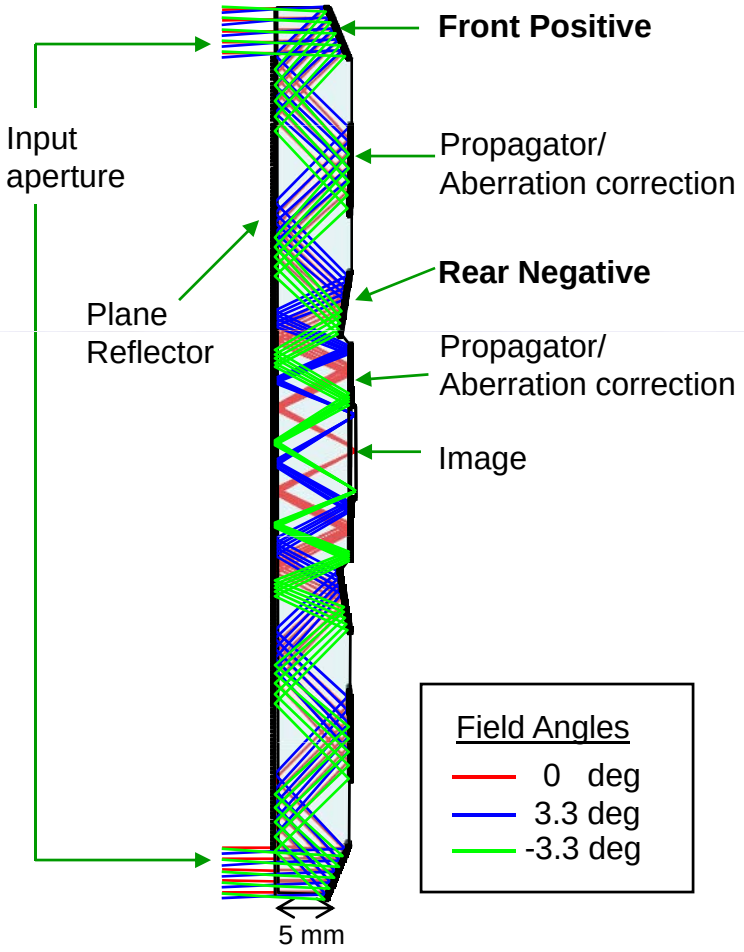

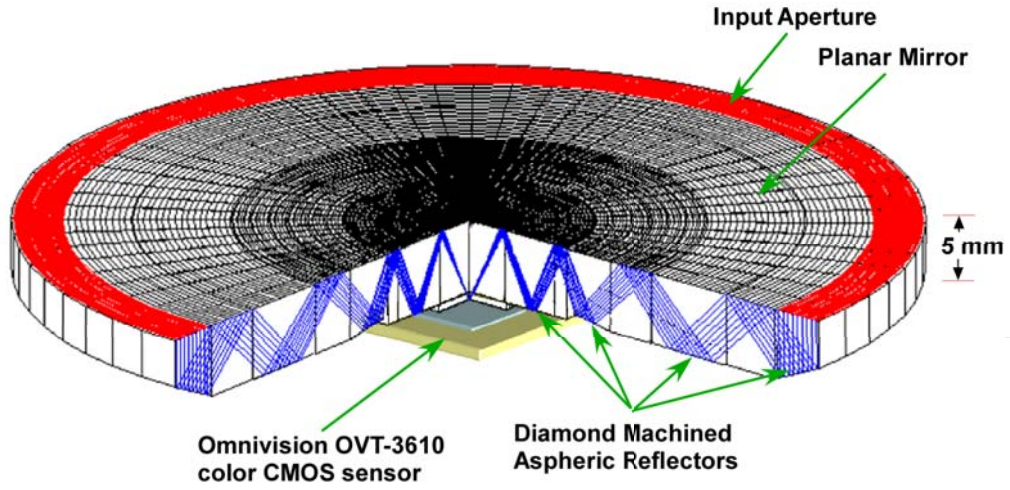

- **38 mm effective focal length folded into 5mm track**
- **60mm diameter, effective circular aperture = 27.3 mm**
  (20% aperture efficiency)
- **Image NA = 0.71**
- **Single-side features**
- **Back focal length ~0.5mm**
- **FOV = 0.12 rad**
- **1280 x 960 pixel**
- **$F/\#_{eff}$= 1.40**

E. J. Tremblay et al., "Ultra-Thin Cameras Using Annular Folded Optics", *Appl. Opt.* 46, pp. 463-471 (2007).

Top Award, Optical Research Associates' Student Optical Design Competition (2005)

Simulated Performance

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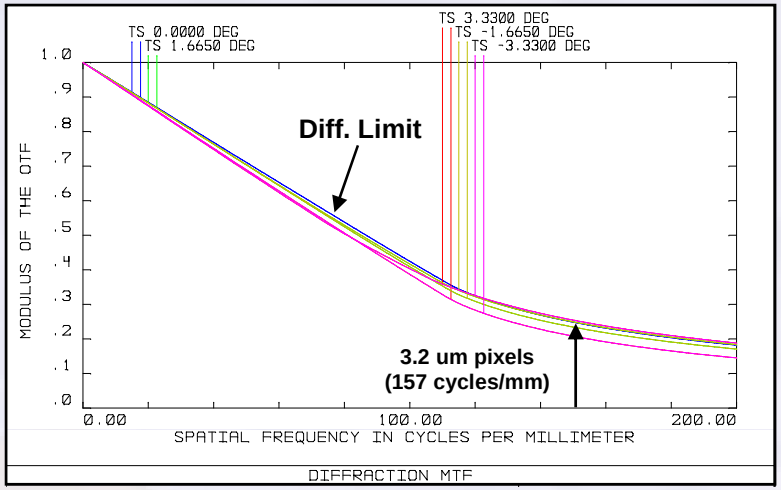
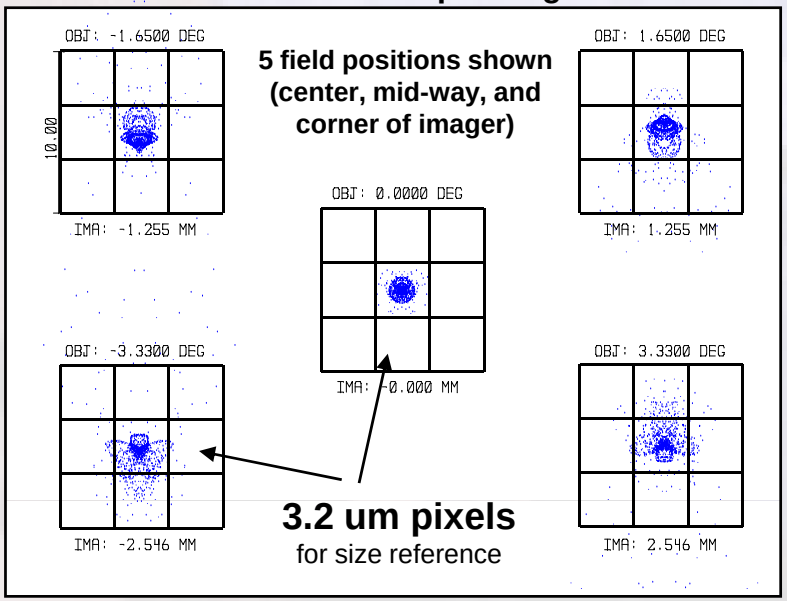
Monochromatic MTF



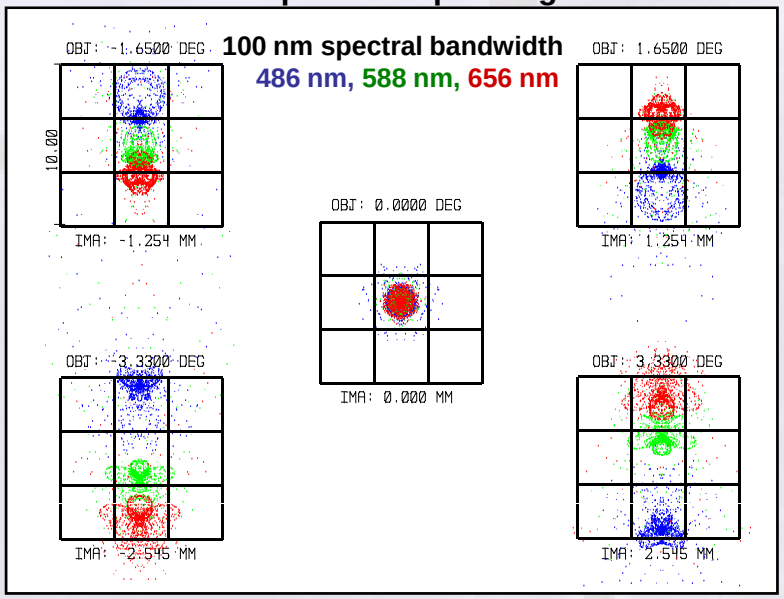
- **Diffraction limited monochromatic performance**
- **Almost achromatic: Refraction at flat input face**
  ~8 µm lateral color over visible band (CaF2)
  (Hollow air gap version totally achromatic)

Monochromatic spot diagram



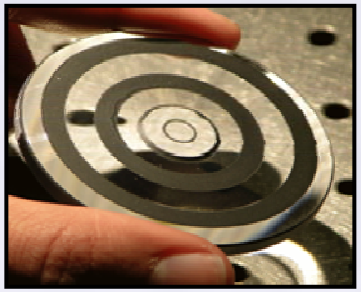
Monochromatic design diffraction limited (geom. spots misleading)

Broadspectrum spot diagram



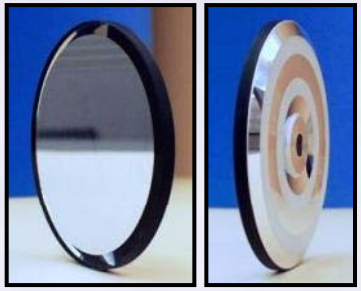
Visible spectra: +/- 1 pixel lateral color from refraction at input face
(slight wavelength-dependent magnification)

Lens Fabrication and First Results



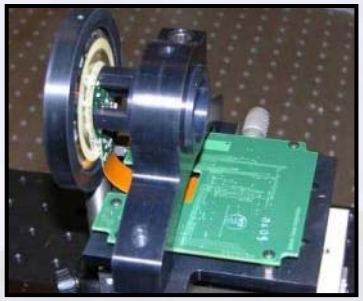
(1) Diamond-turn lens blank

Fresnel Technologies standard process, except that
Entire surface roughed and blackened before fine turning
Key spec is thickness, 5 microns



(2) Patterned double-sided reflector coating

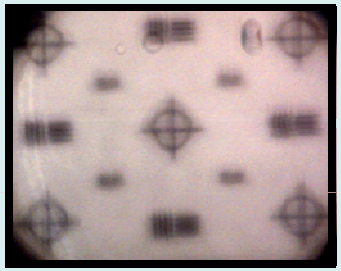
Silver metal mirrors done by outside vender
Dielectric coating from Iridian Spectral Tech is IR cold mirror
Total light throughput is 30% w/o AR coatings and 8 bounces



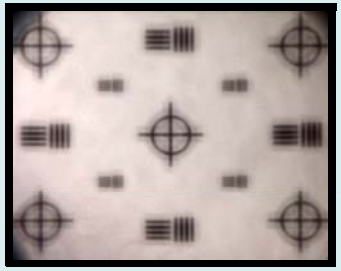
(3) Active alignment of CMOS sensor

Optical bench alignment
Hard UV adhesive for fixed focus camera
Index matching to CMOS sensor to disable microlenses

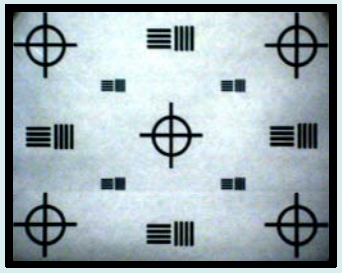
Results:



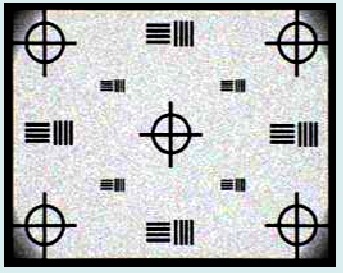
PMMA Test



1st CaF_2 Lens
(thickness errors)



2nd CaF_2 Lens



Zemax Prediction

Packaged Eight-Reflection Camera

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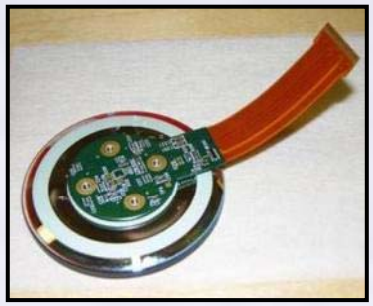


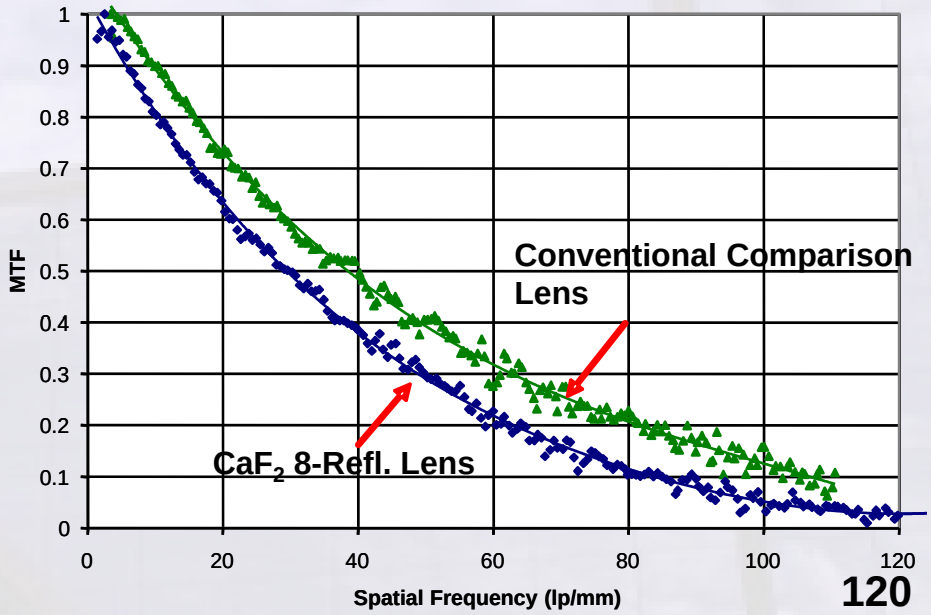
Fully functional fixed-focus camera

- ***Rigiflex PCB holds all electronics under 1 mm***
- ***Strain relief with soft UV epoxy & silicone adhesive***
- ***Ready to mount into plastic case***

Thickness comparison with equivalent conventional camera

Fully-packaged prototype
Including USB interface to PC
(package by DFC)

Measured Modulation Transfer Function



120 lp/mm

Conventional vs. Eight-Reflection Camera

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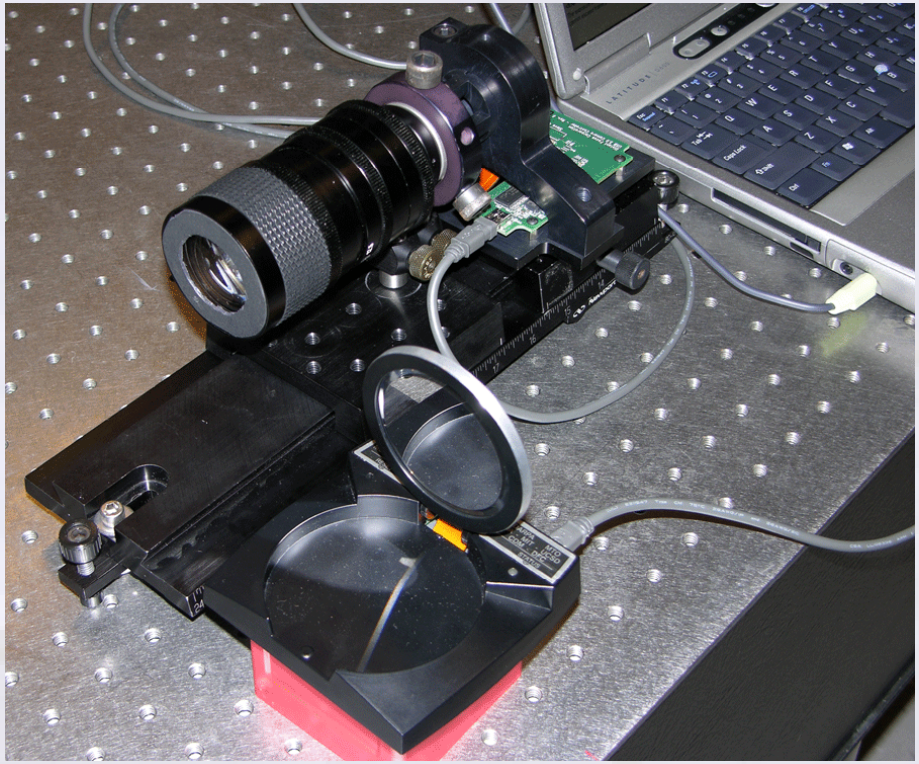
Deep Color Test Scene

Stacked resolution targets
2.5m distance with 7 cm steps
Plus color textbook
Fluorescent illumination



Conventional imager for comparison

Tokina F/1.2 zoom 12.5-75mm, set to 40 mm
Aperture constrained to 35 mm diameter
Identical CMOS sensor and interface board

Resolution and Color Image Comparison

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Conventional Tokina lens

+7cm

Focus (250 cm)

-7cm

-14cm

Unprocessed 8-Reflection Lens

Spatial resolution: Similar at ~120 lines/mm

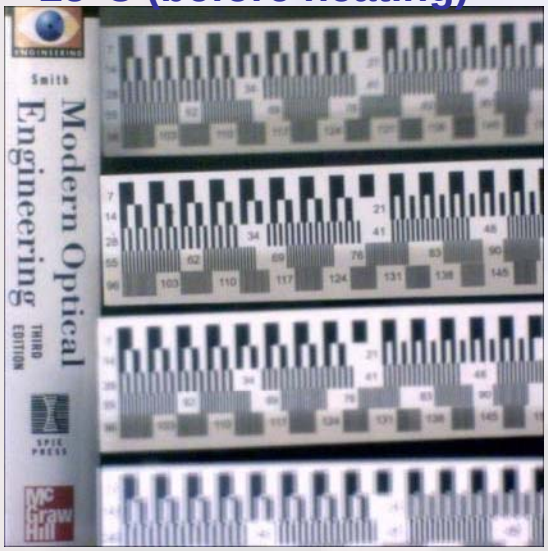
Color fidelity: Identical (following standard post-detection color balancing)

Depth of field: CMR lens (right) is revealed by defocus (NA = 0.7)

Thermal testing

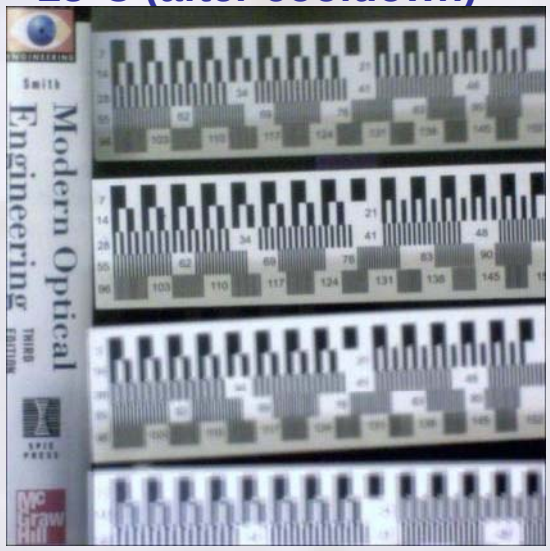
Thermal test setup:
- Same stepped target & lighting as resolution & depth of field test
- Images taken through uncoated oven door window
- Camera heated from 77°F to 140°F, and cooled to about 50°C with ice.

25°C (before heating)



After 90 minutes at 60°C

23°C (after cooldown)



Results from testing lab prototype camera
- Minor lens defocus (~1% closer) from initial position, plus slight tilt due to plastic hinge.
- CMOS imager has strong color variation (images shown corrected by autobalancing in photoshop)
- No apparent damage to camera after testing