Synopsis of Technical Report:

Optical design, fabrication and evaluation of optical systems using free-shaped prism

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Introduction:

In this paper, the design features, fabrication, measurement, and evaluation when using free-shaped surfaces in an image capturing optical system were described. In this synopsis, important info is summarized.

Conventional co-axial optical systems and their limitations.

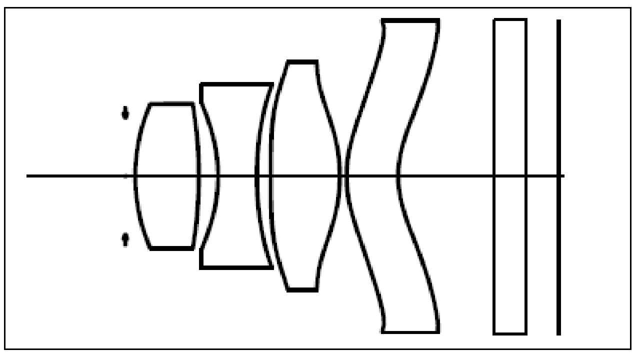

Fig 1. an typical example optical design for a mobile-phone camera lens, for 3 Megapixel class and above.

Limitations:

1. Hard to reduce thickness due to number of elements (3-4) required to achieve reasonable image quality.
2. Large chief ray angle from the edge of the field on the detector, result in insufficient edge brightness.
3. High precision required in aspheric lens manufacture and assembly, result in high costs and low yields.

Introduction of Free-shaped Prism

Co-axial arrangement of optical elements conflicts with the requirement of making the system thinner. Therefore, system can be made a lot thinner by folding the optical path with a combination of reflecting/refracting surfaces with optical power, Fig 2.

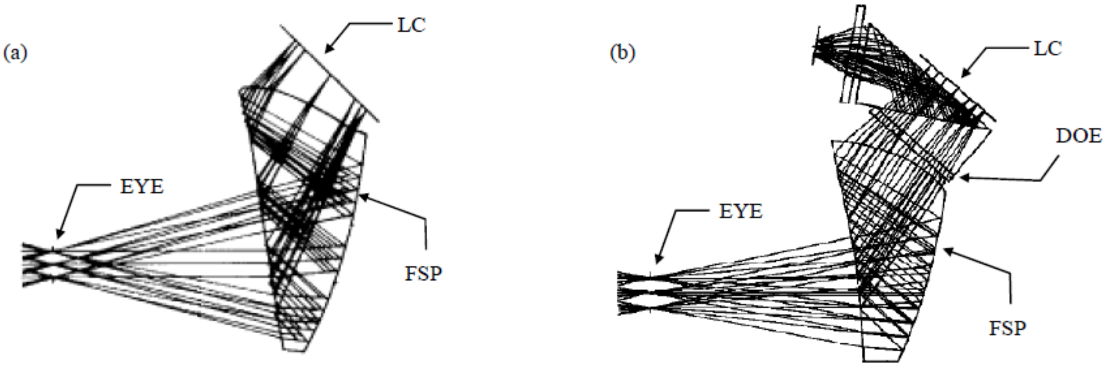

Fig 2. Two example optical system using free-shaped prism for head-mounted displays.

Decentered reflecting surfaces causes off-axial aberrations:

- Off-axis astigmatism
- Off-axis coma
- Off-axis distortion
- Off-axis tilting of the image plane

To correct these aberrations which are not presented in co-axial systems, more degrees of freedom are given to designing the surface shapes, i.e. using rotationally asymmetric curved surface (free-shaped surface).

In the paper, they used a XY polynomial surface profile:

$$z = \sum_{n=0}^{k} \sum_{m=0}^{n} C_{nm} x^m y^{n-m}$$

Alternative surface profiles used in free-shaped prisms include Anamorphic Asphere (AAS), Zernike Polynomial (ZRN), XY Polynomial (XYP) and etc.

Optical Design of Mobile-Phone Camera Lens using Free-Shaped Prisms

1. Target Specifications:

Table 1 Target specifications

Sensor size	1/4inch
Focal length	3.6 mm, effective (equivalent in 35mm photography)
Fno	2.8, effective
Optical thickness	6.0 mm or less
Optical performance	compatible with 3 megapixels or above

2. System Diagram

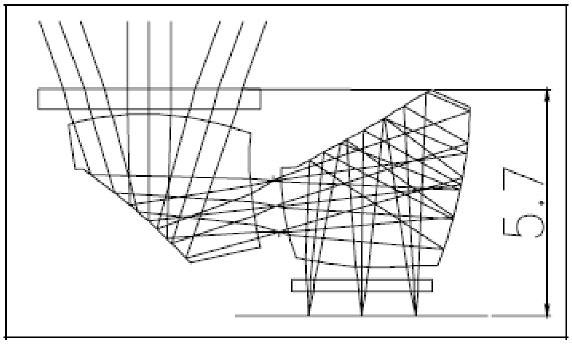

Fig 3. Designed System

3. System Characteristics

1) System uses a retrofocus design.
   - Chief-ray angles are more uniform across the field of view, produces more uniform image shading.
   - Folds the long optical path into small thickness, which is not possible in co-axial systems.
   - Long optical path length reduces power and aberrations caused at each surfaces as well as manufacturing variations.
2) Reflecting surfaces contributes greater amount of optical power.
   - No chromatic aberrations on reflecting surfaces.
   - Chromatic aberrations are very well corrected without using combination of different materials.
3) High optical performance
   - Close to diffraction limit
   - High performance maintained from the center to the edges

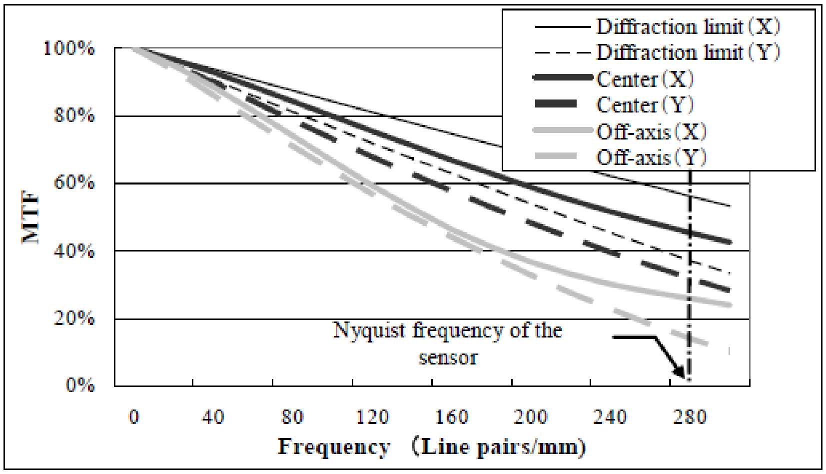

Fig 4. MTF Performance of the design

4) Well-controlled assembly tolerances
   - MTF deterioration less than 10% when decentering is 20um

Measurement and Evaluation

1. Evaluation of Shape Errors

Surface error measurements in free-shaped prisms are similar to evaluating axis-symmetric aspherical lenses, using commercial profilometer.

Shape Error Evaluation Procedures:

1) Fit the designed surface equation to the measured point clouds using least square method
2) Evaluate the rms and PV error values of the residual surface variation

2. Evaluation of Decentering Errors

The decentering errors in free-shaped prism can't be evaluated using conventional method due to the geometry of the prism. The paper presents using a reference glass block with similar and known shape to reconstruct the free-shaped prism's geometry.

Reference glass block preparation:

- Fabricate a glass block matching the shape of the free-shaped prism, in which surfaces corresponding to the surfaces of the free-shaped prism to be designed were formed as planar surfaces.
- Measure the angles formed by each surface of the glass block with high precision using auto-collimator

Measurement procedures:

- Mount both the free-shaped prism and the glass block on the rotation stage with corresponding surfaces aligned.
- Position surfaces under inspection close to orthogonal to the measurement probe of profilometer
- Measure both surfaces on the prism and on the glass block in the same coordinate system.

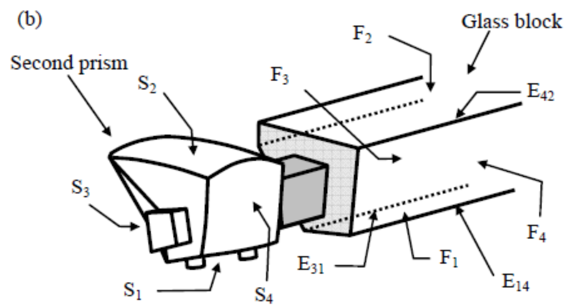

Fig 5. Layout diagram of the prism and glass block

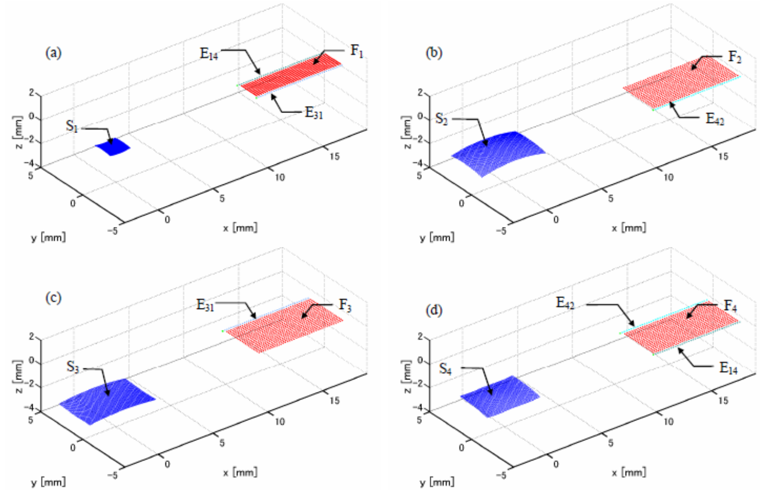

Fig 6. Measured results

Decentering Error Evaluation procedures:

1) Using the premeasured angles formed by the glass block surfaces, reconstruct the geometry of the point cloud of the glass prism.
2) The geometry of the free-shaped prism can them be formed using the coordinate system of the glass prism.
3) Local coordinate origins of each surface are calculated as in evaluating shape errors.
4) Evaluate decentering and tilt errors of each surface.

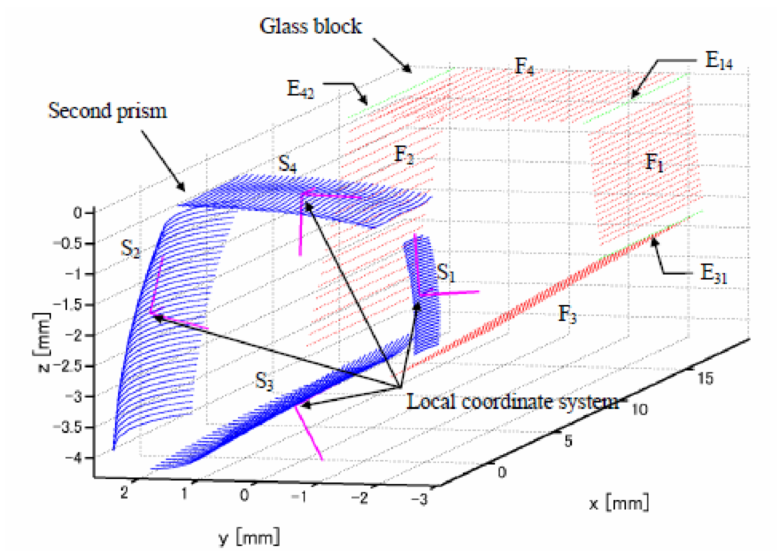

Fig 7. Reconstructed coordinate system

Optical Performance and Prototype:

In the paper, simulations of optical performance were performed using data from measuring and evaluating a prototype prism. The simulation results matched with the measured results very well.

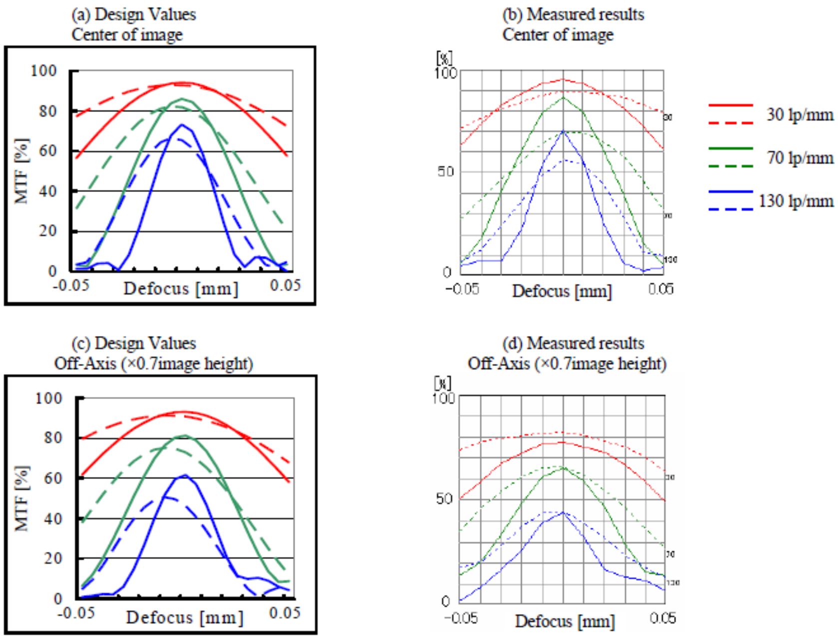

Fig 8. MTF for simulated and measured results

Fig 9. Prototype and picture taken with the prototype

Conclusions:

The paper presented a good design of free-shaped prism application as a compact mobile-phone camera lens. It showed that the use of free-shaped surfaces is very promising in a lot of optical systems. More importantly, the paper presented a method to measure and evaluates this novel type of system.