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Optical analysis of miniature lenses with curved imaging surfaces

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Miniature cameras for consumer electronics and mobile phones have been, and continue to be, in fast development. The system level requirements, such as manufacturing cost, packaging, and sensor characteristics, impose unique challenges for optical designers. In this paper, we discuss the potential optical benefits of having a curved image surface rather than a flat one. We show that curved sensor technology allows for optically faster lens solutions. We discuss trade-offs of several relevant characteristics, such as packaging, chief ray angle, image quality, and tolerance sensitivity. A comparison of a benchmark flat field lens, and an evaluation design imaging on a curved surface and working at $f/1.6$, provides useful specific insights. For a given image quality, departing from a flat imaging surface does not allow significantly reducing the total length of a lens.

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1. INTRODUCTION

Miniature camera lens modules are integrated in a variety of portable devices, including cell phones, tablets, laptops and spy cameras, to mention common applications. The photographic performance of these tiny, always ready-for-action lenses, is remarkable as it rivals that of single-lens reflex cameras. Mobile camera technology and devices is a very fast growing field in the imaging market and is impacting the industry by decreasing the production of larger photographic cameras.

The design and packaging of a miniature camera lens module imposes optical design challenges. A traditional objective lens can not be simply scaled down as a lens solution due to fabrication constraints, materials properties, manufacturing process, light diffraction and geometrical aberrations. The increasing demand for thinner, lighter, and low-cost mobile cameras has thus forced the development of new manufacturing technologies and of lens design solutions with high performance.

The optical advantages of using a curved image sensor have been already discussed in the literature. A general conclusion is that a curved image surface allows designing simpler, more compact, and lower-cost optics [1–3]. Recently several researchers have made progress toward developing curved sensors [4–8].

The curved sensor technology for the format which is suited for mobile cameras is near to being commercialized. On the 2014 VLSI Symposia, Sony officially released two curved sensors. One has a diagonal of 43 mm, which is equivalent to a full-frame sensor. The other has a diagonal of 11 mm, which corresponds to a 2/3 in. sensor format [9]. For reference, a flat 2/3 in. sensor has been used in the Nokia Lumia 1020 smart phone camera module.

In this paper, we analyze how allowing for a curved imaging surface impacts the lens design of compact miniature lenses for mobile applications. In Section 2, we highlight typical optical design specifications of state-of-the-art mobile camera lenses. We derive design requirements by comparing products in the market, from patent data, and from publications in the mobile platform optical design and fabrication sector. We review the first-order imaging properties and discuss aberration correction in this class of miniature lenses. In Section 3, we examine how a curved image surface can benefit the lens design of mobile cameras. In Section 4, we show lens design examples for both flat and curved image surfaces. Section 5 provides a detailed comparison of the designs presented in the previous section. We find that a curved image surface allows producing an equivalently performing design with faster $f/\#$ than a conventional design. We also show that other relevant characteristics, such as aberration balancing, image quality, and chief ray incidence angle on the sensor, are favorably impacted. In addition, we discuss distortion aberration as it relates to a curved imaging surface. Finally, we demonstrate improved sensitivity to manufacturing tolerances. Section 6 concludes this paper.

2. REVIEW OF MODERN MOBILE CAMERA LENSES

In this section we present typical optical design requirements and trade-offs of state-of-the-art mobile camera lenses. First, the camera specifications of smart phones from major brands (Apple, Samsung, Nokia, Sony, LG, and HTC) were studied. We found a few trends in the products available on the market:

1. Five lens elements are often used.
2. The image sensor pixel size varies between 1.1 and 2.0 µm.
3. Typical image sensor format is 1/3 in. (6 mm diagonal). The output image resolution is usually 8–12MP depending on the pixel size.
4. The field of view (FOV) of the mobile camera is large. Common FOV values are 65–75 deg.
5. The mobile camera lenses are designed being optically fast. The $f/\#$ varies between 2.0 and 2.2.

Peter Clark provides a historical overview of patented designs and points at several interesting characteristics of miniature camera lens designs [10,11]. Here we focus our patent search on lenses that have specifications similar to the smart-phone camera specifications outlined above. The patent database of compact imaging lenses is extensive. In Subsections 2.A and 2.B we discuss first-order imaging properties of these mobile camera lenses and analyze how aberrations are corrected in patented designs.

A. First-Order Properties

There are some important first-order properties to highlight. These are the total track to focal length ratio, the stop position, the working distance, the relative illumination, and the chief ray angle of incidence on the sensor.

The practically achievable ratio of the total length to the focal length in lenses for mobile cameras is between 1.15 and 1.3 [12]. Decreasing this ratio and making the lens a telephoto would be desirable; however, more optical power would be introduced in the individual lenses and aberration residuals would be large.

The chief ray incidence angle (CRA) depends on the stop position and on the amount of pupil spherical aberration. The CRA impacts the relative illumination, which often is set to 50% at the sensor corners. In order to avoid cross talk between adjacent pixels, the CRA is usually limited to no more than 30 deg [10]. Thus lens telecentricity in image space is desirable, but actual lenses are not telecentric. For better CRA control, the aperture stop is placed close to the front of the lens, away from the image plane. The aperture stop position and the strong aspheric next to the image plane generate exit pupil spherical aberration, which reduces the CRA. As illustrated in Fig. 1(a), the chief ray for different field points crosses the optical axis further away from the sensor and thus the CRA is ingeniously reduced. As also shown in Fig. 1(b), the beam footprints from different field points shift at the exit pupil due to the substantial pupil spherical aberration.

B. Aberration Correction

From the aberration correction point of view a mobile lens can be divided into two groups of lenses, as shown in Fig. 2. The front group consists of two or three lens elements. This group provides effective degree of freedom for correcting spherical and coma aberrations, as well as for correcting chromatic change of focus and chromatic change of magnification. The first lens usually carries a substantial amount of positive optical power and therefore its shape determines substantially the amount of coma in the system; as the stop is near or at the first lens

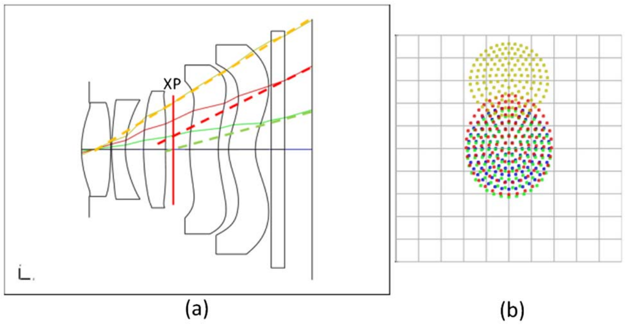

Fig. 1. U.S. patent application 20130258499: layout and spot diagrams at the exit pupil showing substantial pupil spherical aberration.

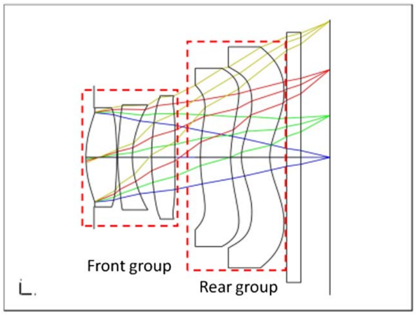

Fig. 2. U.S. patent application 20130258499.

spherical aberration is controlled by the asphericity of at least one of the lens surfaces. To optically relax the lens a minimum amount of optical power is favorable for the first element and then to correct for chromatic change of focus the Abbe number of the first element is maximized, the Abbe number of the second element is minimized, or both. The lens small size also contributes to mitigate the effects of aberration as the wavelength does not scale down with the lens.

The rear group consists of one or two lenses that are strongly aspheric and serve to some extent as field lenses; they correct field curvature and astigmatism of the front group. The rear group also contributes substantial distortion which cancels the distortion from the front group which lacks symmetry about the stop position.

Mobile lenses are notorious by the extensive use of aspheric surfaces. The interaction of multiple aspherics within the design allows for effectively controlling aberrations. Particularly, sharp imaging on a flat surface can be achieved without satisfying the classical requirement of having a Petzval sum nearly zero. The aspheric optical elements located close to the image plane contribute higher-order field curvature and astigmatism. Different orders of the field curvature and astigmatism are balanced to compensate for any residual Petzval curvature [13]. For example, U.S. patent application 20140300975 has a focal length of 3.48 mm and a Petzval radius of about 12 mm. The multiple crossings of the sagittal and tangential field curves indicate the presence of higher-order field curvature and astigmatism, as shown in Fig. 3(b). The last lens is optically weak and has little contribution to the Petzval sum. However, this lens helps flatten the field by introducing higher-order astigmatism and field

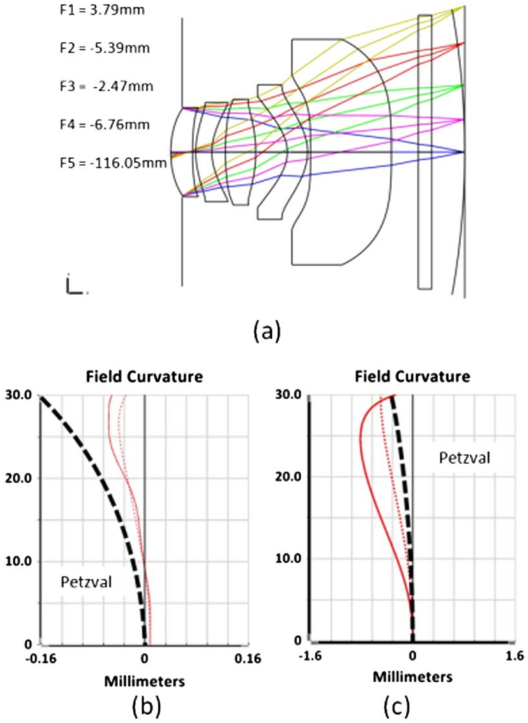

Fig. 3. U.S. patent application 20140300975: (a) Layout, (b) field curvature (scale ±0.16 mm), and (c) field curvature if lens five is removed (scale ±1.6 mm).

curvature. To illustrate this the last lens element in Fig. 3(c) has been removed, the Petzval radius is nearly the same, and the large astigmatism and residual field curvature are then observed.

It is typical to find in the literature excessive, redundant, or illogical use of aspheric coefficients and number of significant figures which can lead to prescription errors and difficulty in analyzing these miniature lens systems.

3. DESIGN ADVANTAGES OF LENSES WITH CURVED IMAGING SURFACES

In this section we mention how a curved imaging surface can benefit the lens design of a miniature mobile camera.

A. Chief Ray Incidence Angle on the Sensor

Since the image plane is curved and the CRA is calculated relative to the image surface normal, the chief ray incidence angle can be significantly reduced, which results in advantage. The chief ray incidence angle still needs to be limited to no more than 30 deg. However, this angle corresponds to a much larger angle in relation to a flat image plane. Consequently, the aperture stop, which is placed close to the front of the lens in a conventional mobile camera, can be shifted.

B. Aperture Stop Position

For a mobile camera with a curved imaging surface the stop location has more flexibility and can be moved to make the lens system to be less unsymmetrical about the stop. Symmetrical or nearly symmetrical lens design forms allow for a more balanced and better aberration correction. Many classical objectives are designed symmetrically around the aperture stop [14]. In a symmetrical optical system all odd aberrations tend to cancel out permitting a higher level of aberration correction.

C. Field Curvature and *F*-Number

In a flat field lens field curvature correction is obtained by introducing negative optical power, and this leads to more overall optical power. Field curvature correction optically stresses a lens and aberration residuals become larger. For a given image quality a lens with a curved imaging surface can have a faster optical speed due to a reduced optical stress. Field curvature aberration is compensated by the curved sensor. An improvement of a one f-stop is a typical gain in speed for comparable imaging performance with respect to a flat field lens.

D. Total Length

The total length of a mobile lens is an important design parameter. It would be attractive if curved sensor technology would allow designing a shorter lens, such as a telephoto lens. However, a shorter lens would require optically stressing the lens and departing more from symmetry. As the aberrations substantially increase with lens stress, the optical speed or FOV would have to be decreased to achieve the same aberration correction. Thus in practice no substantial reduction in length can be obtained from using a curved imaging surface.

4. DESIGN EXAMPLES

For comparison purposes in this section we present two design examples of miniature lenses: one with a flat imaging surface called the benchmark lens, and another with a curved imaging surface called the evaluation lens.

A. Specification

Following the discussion in Section 2, a set of reasonable lens specifications is provided. Assuming 1/3 in. sensor format (6 mm in diagonal) and a FOV of 70 deg, we choose a focal length of 4.5 mm and limit the total length of the lens to 5.5 mm. We design for the visible light from 430 to 656 nm. The f-number is set at $f/2.2$. The specifications are summarized in Table 1.

B. Benchmark Lens

We develop a benchmark lens as follows. The U.S. patent application 20130258499 provides a lens with specifications

Table 1. Design Specifications

Requirement	Value
Sensor format	1/3″
$f/\#$	2.2
FOV [deg]	70
f	4.5
Total length [mm]	<5.5
Distortion	<1%
Number of lenses	5
Materials	COC, OKP4
Edge thickness [mm]	>0.1
Center thickness [mm]	>0.3
Air gap [mm]	>0.1
Surface slope [deg]	<55
Element aspect ratio	<1:5
IR cut filter [mm]	0.2

Table 2. Prescription for the Benchmark Design

Surf	Radi	Thic	Glass	Conic	4th	6th	8th	10th	12th	14th	16th
OBJ	Inf	Inf									
STO	Inf	−0.1742									
2	2.3150	0.5487	F52R		−5.43E − 03	−8.89E − 03	2.41E − 03	−5.37E − 03			
3	−46.17	0.1018			2.84E − 03	−1.91E − 02	2.56E − 03	−1.71E − 03			
4	3.3031	0.2453	OKP4		−8.88E − 02	3.83E − 02	−1.92E − 02	7.62E − 03			
5	1.7092	0.3272			−1.23E − 01	5.05E − 02	−2.04E − 02	5.00E − 03			
6	6.3429	0.6860	F52R		−2.87E − 02	1.26E − 02	−1.60E − 02	1.32E − 02	2.63E − 03	−2.71E − 03	3.11E − 04
7	521.22	0.5740			−4.82E − 02	6.21E − 03	−1.10E − 02	1.85E − 02	−1.26E − 02	5.14E − 03	−6.79E − 04
8	2.8303	0.4901	F52R		−5.18E − 02	4.63E − 02	−7.00E − 02	5.38E − 02	−2.62E − 02	6.87E − 03	−7.35E − 04
9	3.5651	0.5929		−54.19	1.15E − 02	−1.26E − 03	−7.86E − 03	1.25E − 03			
10	2.2306	0.8486	F52R	3.9004	−1.29E − 01	2.04E − 02	6.20E − 03	−4.67E − 03	4.96E − 04	1.49E − 04	−2.42E − 05
11	1.5027	0.4000		−3.2055	−8.67E − 02	2.71E − 02	−5.03E − 03	7.28E − 05	1.23E − 04	−1.76E − 05	7.67E − 07
12	Inf	0.2000	1.517, 64.2								
13	Inf	0.5063									
IMA	Inf										

Table 3. Prescription for the Evaluation Design

Surf	Radi	Thic	Glass	Conic	4th	6th	8th	10th	12th	14th	16th
OBJ	Inf	Inf	0								
1	2.2494	0.4100	F52R	0.1400	1.77E − 03	−5.59E − 03	2.11E − 03	−1.40E − 03	−4.35E − 04	4.84E − 04	−1.86E − 04
2	7.1311	0.1703			1.33E − 02	−7.39E − 03	−3.52E − 04	1.20E − 04	5.87E − 05	−1.19E − 05	−5.17E − 05
STO	Inf	0.0496									
4	6.9383	0.3472	OKP4		−1.24E − 02	−4.55E − 03	5.88E − 03	−1.57E − 03	−5.53E − 04	5.52E − 04	−1.05E − 04
5	2.5203	0.1845			−3.85E − 02	2.67E − 02	−2.26E − 02	1.96E − 02	−9.61E − 03	2.38E − 03	−2.54E − 04
6	3.0512	0.8691	F52R		−1.52E − 02	2.87E − 03	7.73E − 04	−1.59E − 04	−3.32E − 05	−3.92E − 05	1.58E − 05
7	−8.0687	1.0341			−1.47E − 02	3.97E − 03	−5.04E − 03	8.19E − 04	1.00E − 03	−6.13E − 04	1.05E − 04
8	14.4908	0.3906	OKP4		−3.90E − 02	−1.83E − 02	1.93E − 02	−1.28E − 02	1.73E − 04	1.92E − 03	−4.93E − 04
9	8.5320	0.4696			−7.03E − 02	3.01E − 02	−1.30E − 02	1.74E − 03	−1.23E − 04	1.18E − 04	−2.23E − 05
10	3.3880	0.4499	F52R		−1.65E − 01	3.04E − 02	5.26E − 04	2.31E − 04	−1.76E − 03	6.42E − 04	−6.73E − 05
11	2.5782	0.4820			−1.43E − 01	3.69E − 02	−8.28E − 03	9.85E − 04	−4.04E − 05	−3.76E − 06	3.28E − 07
12	Inf	0.2000	1.550, 55.0								
13	Inf	0.4500									
IMA	−10.8615	5.8702									

close to the required in Table 1 and is a good starting point for such a benchmark lens design. The lens has a focal length of 4.109 mm and a FOV of 69.78 deg operating at $f/2.2$. We scaled up the lens and replaced the model materials from the patent application with real materials. We used Zeonex F52R (nd = 1.5333 vd = 53.5) and OKP4 (nd = 1.6059 vd = 26.9). The lens was optimized while preserving the initial design form. The final layout of the benchmark lenses is shown on top of Fig. 4. The lens prescription is given in Table 2.

C. Evaluation Lens

We considered and optimized a variety of lens forms and arrived at the lens we call the evaluation lens. In our optimization we allowed the curvature of the imaging surface to vary, the individual lens optical power to vary, and the aperture stop location to also vary. We found that the optimum location of the stop was between the first and second lenses for a given system total length. Since no correction for field curvature was necessary, a faster lens, $f/1.6$, with excellent image quality was found. The layout of the evaluation lens is shown at the bottom of Fig. 4. The prescription is given in Table 3.

5. LENS COMPARISON

In this section we illustrate the advantages of the curved image surface by comparing the optical performance of the benchmark design and the evaluation design.

A. First-Order Properties

The layouts of both benchmark and evaluation lenses are shown in Fig. 4. Both designs have similar configuration: the first three lenses provide most of the optical power while last two elements are weak correcting lenses.

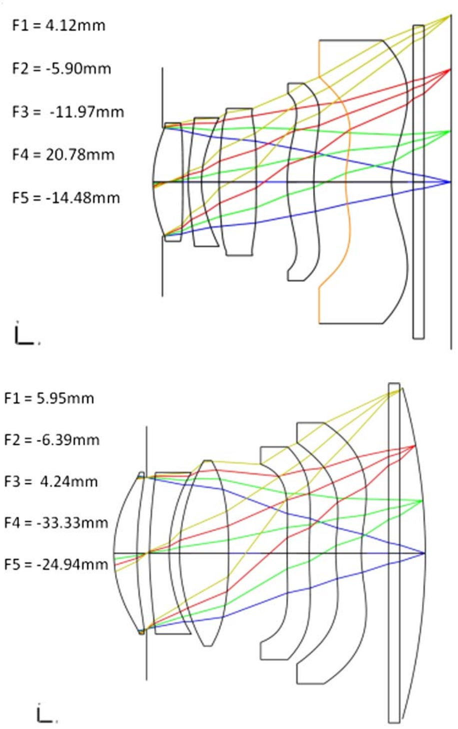

Fig. 4. Layout: (top) benchmark design; (bottom) evaluation lens.

The power distribution in these two lenses is different. Consider the paraxial refraction equation:

$$n'u' = nu - y\phi. \tag{1}$$

In this equation $n'u'$ and nu are products of the index of refraction and paraxial marginal ray slope before and after refraction at the surface, y is the marginal ray height at the surface, and Φ is the surface optical power. Consequently, the weighted surface power is given by the difference between the marginal paraxial ray slope before and after refracting at the surface. We normalize the total weighted power to 1. For each optical element we plot the difference between the marginal paraxial ray slope before and after passing through the element. The plot in Fig. 5 provides an indication where the optical power originates within the system.

B. Field Curvature

The field curves of the benchmark design are typical for a flat field mobile lens and are shown in Fig. 6 on the left. The Petzval radius is −19.12 mm. The residual field curvature is corrected by balancing higher orders of the field curvature and astigmatism. The field curves are wavy with multiple crossing across the FOV. In contrast the field curves for the evaluation lens are much more smooth and are shown in Fig. 6 on the right. The Petzval radius is −8.74 mm (about 2 times the focal length); this clearly indicates that the field curvature is compensated by the curved image surface. The image surface radius of curvature is −10.86 mm.

C. Image Quality

The polychromatic modulation transfer function (MTF) was calculated in Zemax lens design software [15] and shown in Fig. 7. The pupil is sampled with a 128 × 128 ray grid. The MTF of the evaluation lens is calculated on the curved image surface. Both lenses show very good performance over the entire FOV with an average MTF of about 70% at 112 lp/mm (gray-scale Ny/4 frequency for a 1.1 μm pixel) and over 45% MTF at 225 lp/mm (gray-scale Ny/2 frequency for a 1.1 μm pixel). However, the lens designed for the curved image sensor is about one f-stop faster compared to the conventional design. We think it would be impossible to achieve similar aberration correction for this $f/\#$ for a flat sensor with five lens elements. In the benchmark lens the MTF at high frequencies varies significantly with the field angle. The MTF of the evaluation lens is more uniform over the field.

The limiting aberrations for the evaluation lens are spherical aberration, oblique spherical aberration, and spherochromatism. Figure 8 shows the variation of spherical aberration and oblique spherical aberration across the field of view.

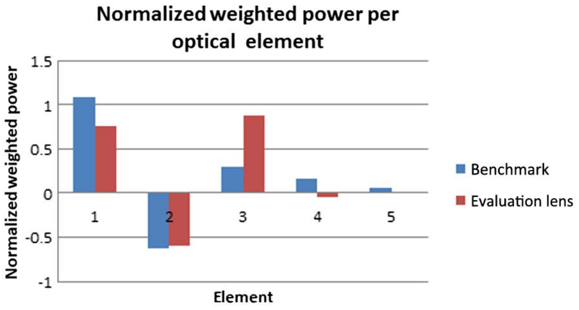

Fig. 5. Normalized weighted power per optical element.

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