The optical advantages of curved focal plane arrays

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Abstract: The design of optical systems for digital cameras is complicated by the requirement that the image surface be planar, which results in complex and expensive optics. We analyze a compact optical system with a curved image surface and compare its performance to systems with planar image surfaces via optics analysis and image system simulation. Our analysis shows that a curved image surface provides a way to lower the number of optical elements, reduce aberrations including astigmatism and coma, and increase off-axis brightness and sharpness. A method to fabricate curved image focal plane arrays using monolithic silicon is demonstrated.

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References and links

Digital photography has advanced at a fast pace over the last two decades [1] resulting in an increasing demand for digital cameras for mobile imaging, video conferencing and biosensing [2]. Compared to the rapid progress in digital image sensors, the optical systems of digital cameras have evolved at a much slower pace. One factor that constrains the design of optical systems for digital cameras is that the image surface, i.e., the Petzval surface, must be planar such that the image can be recorded using a planar silicon focal plane array (FPA). This constraint leads to off-axis aberrations that include astigmatism, field curvature and coma. These need to be corrected using additional optical elements, complicating the optical system design and resulting in a higher cost. If the requirement that the image surface be planar can be relaxed, simpler, more compact and lower-cost optics can be used.

Schmidt proposed the use of curved FPAs to remove spherical aberrations caused by a spherical mirror together with an aspheric corrector [3]. Large field-of-view (FOV) cameras [4], spherical imagers [5], artificial retina and biomimetic optical sensors [6] have been proposed or realized with curved FPAs. Because such curved FPAs require specialized processing [7], or can be manufactured only with a large radius of curvature ($r>75$mm) using tiling, bending or selective etching of CCDs [8-10], the scope of research on curved FPAs camera systems has been limited to large, high-end optical systems such as astronomical telescopes [8, 11]. Recently, Dinyari et al. [12] demonstrated a method to curve monolithic silicon into a hemispherical shape. This method may be an economically viable method to manufacture curved FPAs with a radius of curvature that is useful for consumer digital cameras. In this Letter, we analyze the optical performance of hemispherically curved FPAs using a system level analysis [13, 14], and demonstrate their potential for excellent optical performance in conjunction with simple optical systems.

When designing a compact camera system consisting of one to three lens elements, the designer is mainly concerned with reducing chromatic and spherical aberrations, distortion, off-axis illumination fall-off and field curvature. The latter causes astigmatism and affects the image FOV. It is corrected using shaped lenses and an increased number of lens elements. A camera system with a curved image surface, on the other hand, provides more freedom in choice of lens shapes. In addition, a lower number of lens elements suffices leading to a lower cost and a more compact camera. Furthermore, a curved image surface allows for a symmetrical arrangement where all points on the image surface are essentially on-axis points, as shown below, which also simplifies design [15]. Here, we compare a camera system with a ball lens and spherical FPA to camera systems that consist of singlet and triplet lenses and a planar FPA and illustrate the benefits of the curved FPA.

The three systems considered (Fig. 1(a)-(c) insets) have an identical F-number of 3.5. System I consists of a plano-convex lens with a 6.25mm-diagonal planar FPA. System II [16] is a Cooke triplet, typical for low-end photographic cameras [17], with a 5.9mm-diagonal planar FPA. System III is based on a hemispherical FPA (radius-of-curvature $r=5.87$mm) and a 4mm-radius ball lens. BK-7 is used as lens material for the three systems. Unless specified, the optical design and analysis were performed using a weighted sum of the response at the wavelengths $\lambda=656.3$nm, 486.1nm and 587.6nm, with a relative weight of 1, 1, and 2, respectively.
The modulation transfer function (MTF) for each of the three systems is shown in Fig. 1. It is clear that system I performs poorly compared to systems II and III. The MTF of system I is significantly smaller and, in particular, the off-axis response (at 0.4 of the FOV in green, and at 0.7 of the FOV in blue) is far inferior to the on-axis response (red). System III, on the other hand, is superior to system II, especially off-axis and for the radial MTF (dashed dot lines). The on-axis response of system II is slightly better than that of system III at high sampling frequencies. We note also that the MTF of system III is nearly identical for on-axis and off-axis illumination as expected by the spherical symmetry of the system. System III retains 60% of the on-axis modulation at 68 cycles/mm, corresponding to an optical resolution of 7.4 μm at both the center and edge of the image surface.

In Fig. 2, the on-axis (Figs. 2(a)-(c),(g)-(i),(m)-(o)) and off-axis (at 2mm image height, Figs. 2(d)-(f),(j)-(l),(p)-(r)) point spread functions (PSFs) for λ=450nm, 550nm and 650nm are shown for the three systems, using system simulations of the imaging system [18]. The advantage of a symmetric optical system with a curved FPA is clear: all image positions are on-axis and this significantly suppresses coma. The off-axis PSF of system I (Figs. 2(d)-(f)) shows a large degree of aberration compared to the other two systems. The off-axis PSF of system II (Fig. 2(j)) exhibits a double peak at λ=450nm and coma at all wavelengths (Figs. 2(j)-(l)). In contrast, the PSF of system III has a single peak (Figs. 2(p)-(r)). The PSF of system III is clearly more invariant with respect to wavelength and image height, which in turn leads to superior image formation.

The other fundamental monochromatic aberrations, i.e. astigmatism, field curvature and distortion are significantly reduced by use of a curved image surface. In Fig. 3, the astigmatism field curves of systems I and II show the presence of astigmatism and differences between the sagittal (solid lines) and tangential (dotted lines) focal planes (Figs. 3(a)-(b)). In system III (Fig. 3(c)), the sagittal and tangential focal plane are identical, such that no astigmatism is present. We note that the astigmatism ray curves are shifted because the best focal plane is shifted to minimize spherical and chromatic aberrations.
Fig. 2. Point spread functions for (a-c,g-i,m-o) on-axis and (d-f,j-l,p-r) off-axis (2mm image height) points. (a-f) show PSFs for System I, (g-l) for System II and (m-r) for System III.

Fig. 3. Ray curves of astigmatism field curvature of (a) System I, (b) System II and (c) System III. Tangential field curvature (dotted lines) and sagittal field curvature (solid lines) are shown together.
Due to the symmetrical design, all chief rays in System III pass through the optical center, O (see Fig. 4(a)), such that there is no distortion. The mapping of image points in three-dimensional space onto the curved FPA is done as follows. Suppose that the image point on the curved FPA, \( P(p_x,p_y,p_z) \), is transformed to the image point, \( P' \), on the virtual planar image surface. As shown in Fig. 4(a), when \( \overrightarrow{OP} = \overrightarrow{OP}/\cos \theta = (f/p_z)\overrightarrow{OP} \) and \( P(p_x,p_y,p_z) \) is mapped to \((f/p_z,f/p_z)\) on the image plane, where \( f \) is the focal length of the ball lens, the transformed image height is \( FP' = f \tan \theta \), which is the paraxial ideal image height. Hence, system III has no distortion regardless of the image height and wavelength, \( \lambda \) (Fig. 4(d)). For comparison, the distortion in image height of systems I and II are shown as a function of image height and \( \lambda \) in Figs. 4(b) and (c).

Figures 5(a), (b) and (c) show the relative illumination intensity of systems I, II and III, respectively. In systems I and II (planar FPA), the intensity of illumination has a \( \cos^4 \theta \) dependence, where \( \theta \) is the angle between the line from an off-axis point to the center of exit pupil with the optical axis. In system III, all pixels are at the same distance to the exit pupil removing a \( \cos^2 \theta \) dependence. In addition, the illumination is incident on the image surface along the normal direction which eliminates another \( \cos \theta \) factor, leading to an overall \( \cos \theta \)-dependence of illumination intensity. We note that the remaining \( \cos \theta \)-factor is approximate and valid only when the off-axis pixels are far (i.e., many pupil diameters) from the exit pupil. Off-axis illumination intensity fall-off is an unavoidable problem in digital cameras because of reduced pixel fill factors and pixel vignetting [19], and is much more severe for a planar FPA than for a curved FPA because in a curved FPA, all chief rays are incident to the image plane at normal angle. Moreover, the illumination fall-off is more severe for complex optical systems with a multitude of reflective surfaces, again favoring curved FPAs because their optics are simpler.
Images projected by the three optical systems were simulated in a radiometrically accurate model using lens design software [20] and imaging system engineering software [18] by taking into account object radiance and lens properties such as relative illumination, geometric distortion and spatially-variant PSFs at various wavelengths. This method enables the analysis of not only the lens systems but the entire imaging systems [13]. An object image, shown in Fig. 6(a), is placed in the object plane and projected by the three systems. The image of system I (Fig. 6(b)) exhibits barrel distortion and reduced sharpness as expected based on the MTF analysis. The images obtained for systems II (Fig. 6(c)) and III (Fig. 6(d)) are similar in image quality. However, system III provides a sharper image for off-axis locations as expected from the MTF analysis. System III also delivers a brighter image for off-axis pixels.

The design of simple and compact camera systems with curved FPAs has not received much attention, partly because there are no practical, low-cost techniques to realize such FPAs. The two major challenges are to produce a high-quality curved semiconductor substrate...
suitable to build photodetector arrays and to create patterned circuits [7] on such curved substrate. We recently demonstrated a process to curve monolithic silicon substrates after standard foundry processing to address these challenges [12]. In Fig. 7, we show a curved monolithic silicon die produced by this method. The approach uses a deep reactive ion etch step to microstructure the silicon die into a two-dimensional (2D) network of nodes and springs. The springs allow for local deformation of the die necessary to attain a spherical shape. The resulting die can be stretched to a spherical shape on a latex membrane. The nodes can house the photodetectors and addressing circuitry while the springs serve as mechanical and electrical interconnects. The size of the array shown in Fig. 7 is 1.0cm and the radius of curvature of the curved die in Fig. 7(a) is 1.0cm. This process, discussed in more detail in Ref. 12, can be scaled to wafer-scale for the economical production of curved imagers.

![Fig. 7](image)

Fig. 7. (a,b) Optical micrographs of a fabricated curved silicon die. (a) Curved die on a spherical surface with radius of curvature of 1cm. (b) Detail of the curved die at an off-axis location. (c) Scanning electron microscopy (SEM) picture of an undeformed die.

In summary, we have shown that a curved imager provides a large degree of freedom in the design of the camera system, helps reduce fundamental aberrations and provides better resolution and brightness. This was demonstrated using designs for a simple and compact camera system by a full analysis of the characteristics of digital imaging systems with planar and curved FPAs. Using a microfabrication process that structures a silicon die into a stretchable membrane, it might be possible to produce such curved image plane cameras in a cost-effective manner using foundry-processed silicon.

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