Convex Curved Single-Chip Thin-Film Image Sensors for Distortion-Free Multilens Panoramic Imaging

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Abstract—**We propose a concept of convex curved single-chip thin-film image sensors for distortion-free multilens panoramic imaging. A flexible thin-film transistor active pixel sensor (320 × 240 pixels) with an organic photoconductive film was fabricated using a 15-µm-thick film substrate and laminated on a convex curved plate with a radius of curvature of 16.3 mm to form a curved image sensor. By combining the curved sensor with concentrically arranged three lenses, we successfully obtained wide-angle images without distortions by a simple "cropping and tiling" process.**

I. INTRODUCTION

Panoramic imaging is widely used in areas such as machine vision, robotics, and augmented/virtual reality [1]. In general, panoramic images can be captured by stitching multiple images taken by rotating a single camera or constructing a camera array [2]. However, these methods require a pixel-level alignment of rotational axis/camera positions and complex image stitching processes to correct the remaining slight deviations between images [3].

To solve this problem, we propose the concept of convex curved single-chip thin-film image sensors for multilens panoramic imaging (Fig. 1(a)). Distortion-free panoramas can be generated without pixel-level camera alignment because our curved single-chip solution can capture wide-angle images by a simple "cropping and tiling" process excluding distortions around the edges of the view angle (Fig. 1(b)). In this study, we present the first demonstration of tiled images obtained from curved image sensors using multiple lenses.

II. DESIGN AND FABRICATION

As a thin-film image sensor, we fabricated a thin-film transistor (TFT) active pixel sensor (APS) with 320 × 240 pixels using an organic photoconductive film (OPF) [4]. Fig. 2(a) shows the pixel circuit of the TFT APS. A pixel is composed of three transistors [reset (T_R), amplifier (T_A), and row select (T_S) TFTs] and an OPF. A load TFT (T_L) is placed in each column, and photoinduced electric charges generated in the OPF are read out as a voltage signal through a source follower comprising T_A and T_L.

The cross section of the sensor is shown in Fig. 2(b). A highly heat-resistant polyimide film of 15 µm thickness laminated on a glass carrier was used for the sensor fabrication. After 120-nm-thick silicon nitride and 50-nm-thick aluminum oxide (AlO_x) were deposited to form the bottom encapsulation layer, the TFT circuit was firstly fabricated as follows. A 50-nm-thick molybdenum (Mo) alloy was deposited to form a gate electrode, and then a 200-nm-thick silicon oxide (SiO_x) layer was deposited as a gate insulator. After a 30-nm-thick indium–tin–zinc-oxide semiconductor layer was formed, via holes were opened in SiO_x by reactive ion etching using tetrafluoromethane gas, and then the sample was annealed at 300°C to activate the semiconductor layer. Next, a 70-nm-thick Mo alloy was deposited to form source and drain electrodes, and then an organic passivation layer of 600 nm thickness was formed and thermally cured at 200°C. Finally, a 50-nm-thick indium−tin−oxide (ITO) layer was deposited to form a pixel electrode. After fabrication of the TFT circuit, an OPF was then deposited on a pixel area by thermal evaporation in the following order: a 30-nm-thick $Ir(ppz)_3$ electron-blocking layer, a 100-nm-thick SubPC–dopant (volume ratio of 1:1) bulk heterojunction photoconversion layer, and a 30/70-nm-thick zinc oxide/B4PYMPM hole-blocking layer. Then, an ITO top transparent electrode of ~10 nm thickness was formed by damage-free reactive ion plating. Finally, thin-film encapsulation was performed to prevent water and oxygen permeation into the OPF as follows. A 50-nm-thick AlO_x layer was deposited by thermal atomic layer deposition at a process temperature of 100°C as a high barrier layer. Then, a 600-nm-thick photosensitive organic insulator was spin-coated as a protective layer of AlO_x to prevent water corrosion. After electrode pads were exposed by photolithography, flexible printed circuits (FPCs) were implemented using anisotropic conductive films.

To test the fabricated sensor with the glass carrier, an imaging experiment was conducted by connecting the sensor to the evaluation equipment through FPCs. Images from test charts with a light-emitting diode backlight were projected onto a camera lens and focused on the sensor. As shown in Fig. 3, the image output from the sensor was obtained.

As shown in Fig. 4(a), the sensor was then delaminated from the glass carrier by the laser lift-off process. Fig. 4(b) shows a photograph of the sensor after delamination from the glass carrier. Then, the thin-film sensor was conformally laminated on a cylindrically curved plate with a radius of curvature (R) of 16.3 mm using a 5-µm-thick optically clear adhesive film. Fig. 4(c) shows a photograph of the sensor after curved surface lamination. It was confirmed that no cracks or wrinkles were formed during these processes.

III. IMAGING EXPERIMENT

First, a single-lens imaging experiment was conducted. Fig. 5(a) shows the experimental setup. The curved sensor (R = 16.3 mm) and a curved test chart (R = 700 mm) were concentrically placed, and a single plano-convex lens (Edmund, #48-652) with an aperture (2 mm diameter) was used. Simulation prediction was also conducted using optical simulation software (Ansys, Zemax OpticStudio) under the same conditions as those in the experiment including the curved shapes of the sensor and test chart. Fig. 5(b) shows the simulation and experimental results of the single-lens imaging. The resolution at the center as well as the distortion around the edges in the experimental result were consistent with those in the predicted image, demonstrating that the image was successfully captured using the fabricated curved sensor.

Next, a multilens imaging experiment was conducted. Fig. 6(a) shows the setup of the experiment. The curved sensor and curved test chart were at the same position as that shown in Fig. 5(a). The lens holder was attached to the curved sensor and three lenses were mounted on a lens holder. Fig. 6(b) shows the cross section of the curved sensor with the attached lens holder. The curved sensor, three lenses, and the test chart were concentrically placed, and light shields were placed at a distance of 1.1 mm from the sensor surface to prevent optical crosstalk between the lenses. Fig. 7(a) shows an output image from the curved sensor using the three lenses. Dark regions were observed between the images formed by the three lenses owing to the presence of the light shields, indicating that there was no crosstalk between the lenses. The three areas surrounded by dashed red lines were then cropped to form a tiled image. The cropped area was set so as not to include the distortions around the edges of the view angle. Fig. 7(b) shows examples of images from the single lens and tiled images from the cropped area of the three lenses. We successfully obtained wide-angle images without distortions using the three lenses by a simple cropping and tiling process.

IV. CONCLUSION

We proposed a concept of distortion-free multilens panoramic imaging using convex curved single-chip thin-film image sensors and successfully demonstrated the wide-angle tiled images obtained from the fabricated curved TFT APS in combination with the three lenses by cropping and tiling. Increasing sensor size as well as mounting compound lenses are the next step toward achieving multilens panoramic imaging cameras with enhanced image quality.

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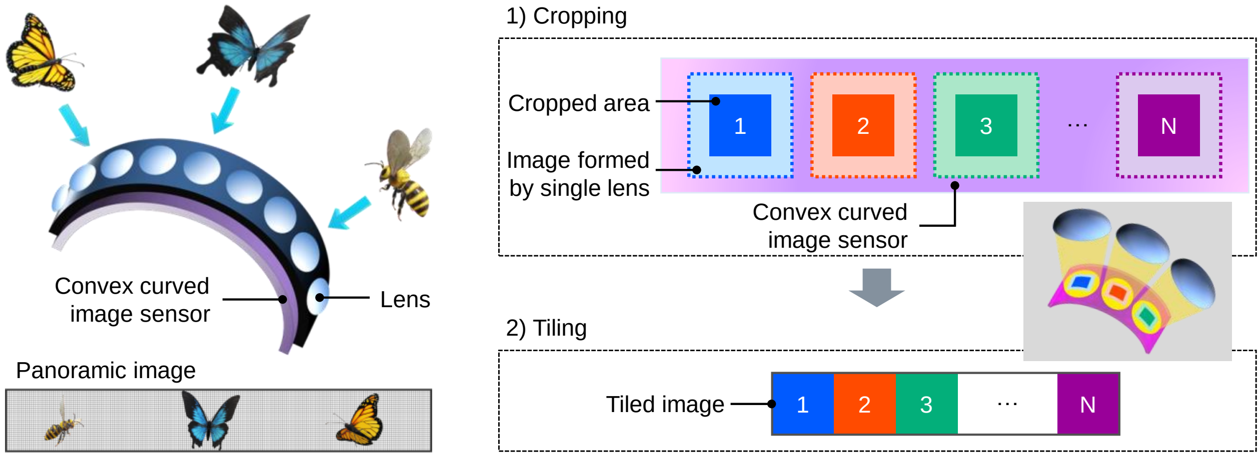
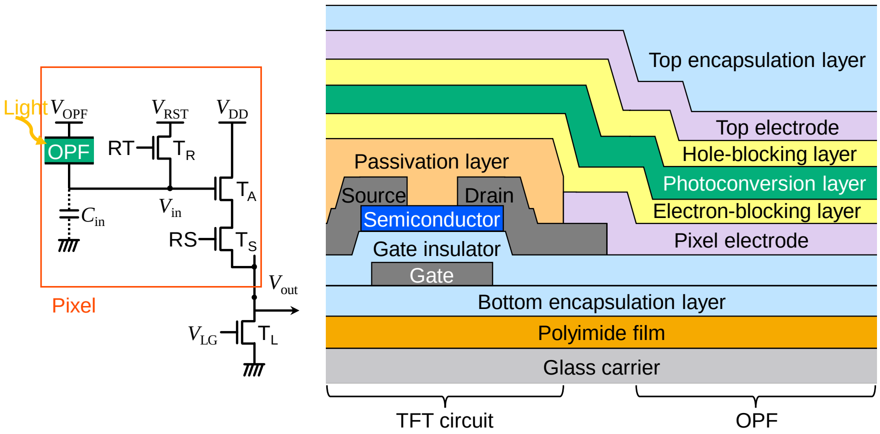


(a)

(b)

Fig. 1. (a) Concept of convex curved single-chip thin-film image sensors for multilens panoramic imaging. (b) Schematic of a simple cropping and tiling process for capturing wide-angle images using curved single-chip image sensors.



(a)

(b)

Fig. 2. (a) Schematic of TFT APS pixel circuit. (b) Cross section of the sensor.

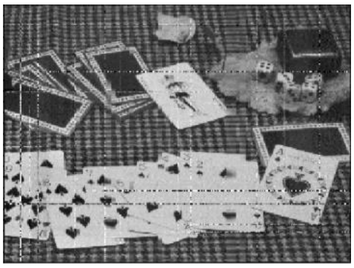
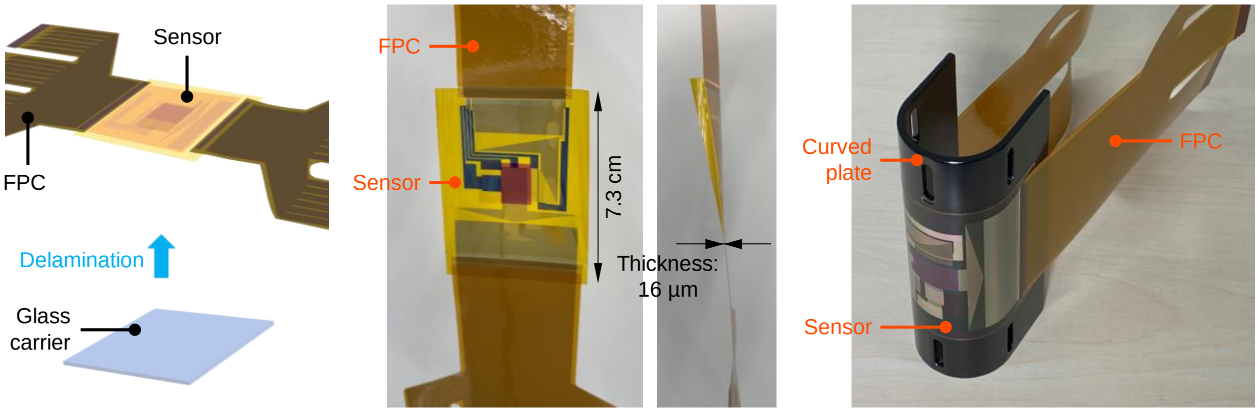


Fig. 3. Image output from the sensor with the glass carrier.



(a)

(b)

(c)

Fig. 4. (a) Schematic of delamination of the sensor from the glass carrier. (b) Photograph of the sensor after delamination from the glass carrier. (c) Curved image sensor fabricated by laminating the thin-film sensor onto the curved plate (R = 16.3 mm).

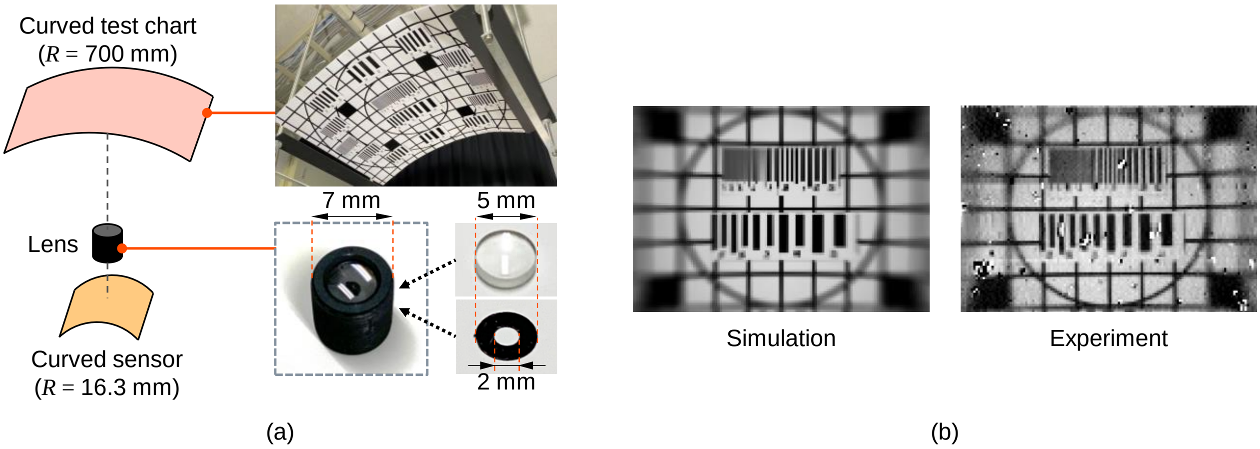


Fig. 5. (a) Setup of the single-lens imaging experiment. (b) Simulation and experimental results of single-lens imaging.

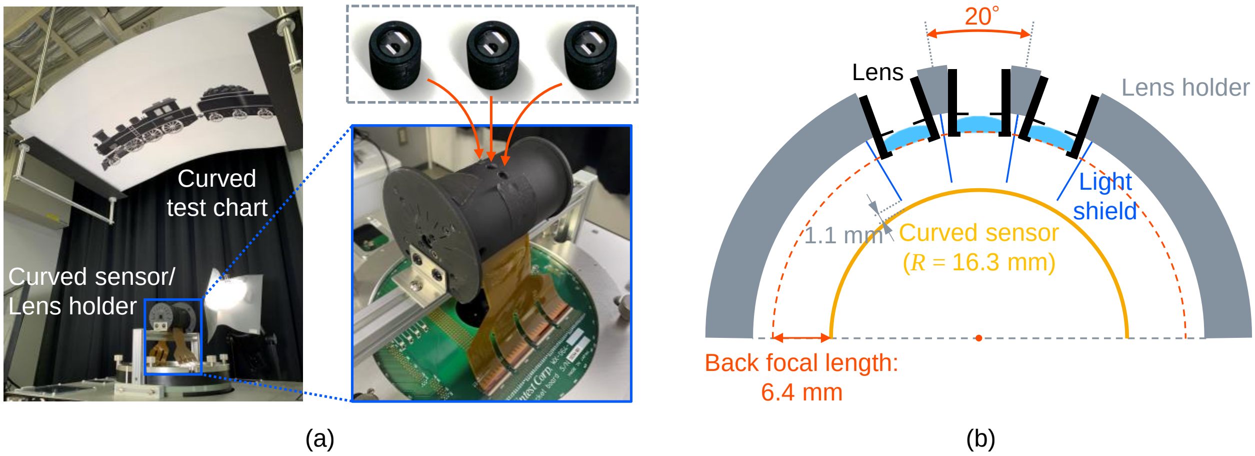


Fig. 6. (a) Experimental setup of multilens imaging. (b) Cross section of the curved sensor with the attached lens holder.

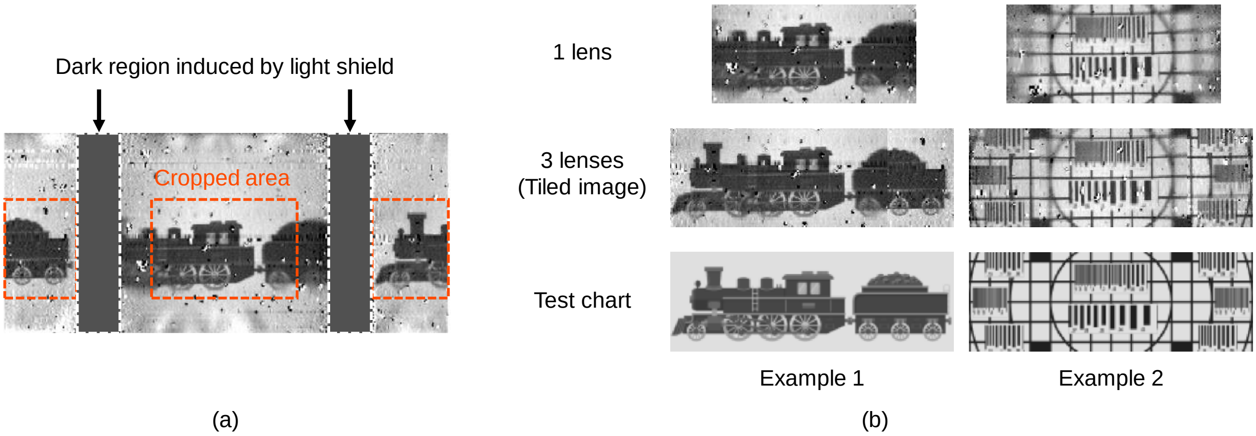


Fig. 7. (a) Output image from the curved sensor using the three lenses. (b) Examples of images from the single lens and tiled images from the cropped area of the three lenses.