# Highly transparent privacy filter film with image distortion

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**Abstract:** We present a novel privacy filter film with transparent micro-cuboid arrays. The privacy filter film, which does not include any opaque materials, rarely affects the normal transparency, whereas it obscures personal information by distorting paths of oblique light rays. The effects of the cuboid size and a gap between the privacy filter and a display are analyzed using a ray-tracing program. The analysis is consistent with the experimental results carried out using the poly-dimethylsiloxane (PDMS) micro-cuboid (100 μm × 100 μm × 200 μm) arrays, which are fabricated by lithography and transfer molding.



**OCIS codes:** (080.2740) Geometric optical design; (130.3990) Micro-optical devices; (230.4000) Microstructure fabrication.

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## 1. Introduction

Recent advances in mobile devices such as smart phones, tablet computers, and PDAs provide individuals with readily accessible on-line information regardless of their locations and timeline. The frequent use of such services, nevertheless, increases the risk of leaking sensitive personal information given that mobile devices (as the word, 'mobile' implies) are commonly used in open spaces [1]. In particular, text-based communications on Facebook and Twitter are vulnerable, as information in text form is readily exposed [2]. To minimize such an invasion of privacy, a privacy filtering technique has been developed [3,4].

Privacy filtering is commonly achieved by employing thin opaque walls which block obliquely incident light [3,4]. However, due to the use of opaque materials, the protection of personal information when using this method comes at the cost of a reduction of the transparency in the normal direction. In order to compensate for the decreased transparency, a high level of energy consumption is required to increase the brightness of the display, leading to a significant reduction in the run-time of mobile devices. To meet the demands of privacy filters without any reduction in transparency levels, scattering and refraction of light can be used as an alternative. These characteristics of light are readily applicable with conventional optical components such as lenses and prisms [5–7]. Further, in accordance with recent advances in micro/nano technology, sufficiently small optical components have been manufactured and applied in various devices, such as solar cells, displays, and light emitting diodes [8–16].

In this work, we propose a novel privacy filter film with transparent micro-cuboid arrays which provides maximum transparency. As light passes through the privacy filter film, obliquely incident light experiences a certain degree of refraction and reflection depending on the refractive index of the micro-cuboid arrays. This process effectively distorts the original images while minimizing the transparency loss in the normal direction. Therefore, the proposed privacy filter film can reap benefits of concealing personal information without consuming additional battery power and while also maintaining the brightness of the display.

## 2. Concepts and experiments

Figure 1(a) shows the top view of the privacy filter, in which transparent cuboids are aligned in lattice spacing design. In Fig. 1(b), light propagates through a transparent cuboid in the normal direction (0°). Light ray paths from character 'B' on the display and characters 'A' and 'C' under the cuboid do not change. Hence, the observed image is identical to the original image. In contrast, Fig. 1(c) shows that the light ray paths are significantly distorted due to the refraction and reflection at boundary of cuboid in the inclined direction (45°). Light rays from character 'A' propagate into two paths; the left path ① is reflected and refracted while the right path ② is only refracted. As a result, the observed character 'A' is shown in double images – one of the 'A' character is inverted. Given that the light from character 'B' experiences two refraction instances, the observed locations of the 'A' and 'B' characters are reversed. The light ray from character 'C' is completely blocked by the total reflection, and it is replaced by an outside source (the inverse character 'F'); thus, no information can be transmitted to the observer in this case.

Figures 1(d)-1(f) show images simulated by the ray-tracing program with SolidWorks [17]. Figure 1(d) depicts the results after the replication, inversion, translation of the location, and the concealment of images, leading to distortion of the overall image. Figures 1(e) and 1(f) demonstrate how the circular image can be definitely distorted using the transparent cuboid array. As one transparent cuboid obscures a clear image in the inclined direction, the cuboid arrays also work as an effective privacy filter. In this way, the proposed privacy filter can hamper any leakage of personal information without relying on any opaque materials.

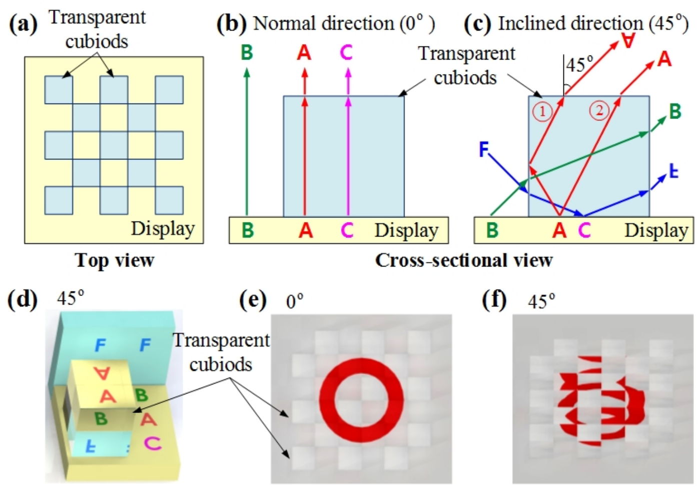


Fig. 1. (a) Top view of the high-transparency privacy filter film. (b), (c) Cross-sectional view of the light ray paths in the normal direction (0°) and in the inclined direction (45°). (d) A simulated image of a single transparent cuboid at 45°. (e), (f) Simulated images of transparent cuboid arrays at 0° and 45°.

In order to confirm the effect of image distortion by the privacy filter, large-scale PDMS rectangular cuboids (1.4 cm × 1.4 cm × 1.8 cm) are fabricated and aligned in a chess board design. The relative size differences between cuboid and space generate area without pattern where no image distortion occurs, which in turn, weakens the overall image distortion effect. Figure 2(a) shows the effect of the PDMS cuboid array when applied to an LCD monitor. In the normal view (0°), the original image is observed without any damages. When an observer views the image at an inclined angle (45°), the image is heavily distorted, and it is almost impossible to track in this case. The PDMS cuboid array is also applied to a printed paper, as shown in Fig. 2(b). Among the three columns of characters, only the first and second columns are effectively distorted, as they are covered with the cuboid array.

Figure 2(c) shows the image distortion effects according to the view angles and the character-to-cuboid size ratios to analyze the effect of cuboid array size. In the normal view (0°), all characters are observed clearly regardless of the size of the characters. At a 30° inclined view, only the smallest character ‘A’ (4:1) is effectively distorted, while other characters are readily recognized. At a 45° inclined view, when the character-to-cuboid size ratio is 10:1, the observed character is partially recognizable; however, the others are completely distorted.

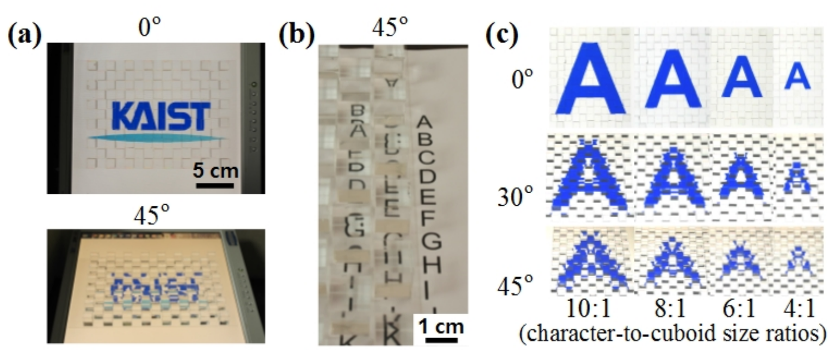


Fig. 2. Experimental results with large-scale PDMS cuboid (1.4 cm × 1.4 cm × 1.8 cm) arrays: (a) normal view (0°) and inclined view (45°) of an LCD monitor, (b) inclined view of a printed paper, and (c) images with different view angles and character-to-cuboid size ratios.

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From this result, it can be inferred that the proper cuboid size is larger than 1/10 size of the characters. Thus, proper size of a cuboid is larger than 400 μm for the effective distortion of these characters considering that the character sizes are 2~4 mm on mobile devices [18]. However, cuboid arrays 400 μm in size are not suitable for a privacy filter, as these arrays are difficult to fabricate and interrupt readability given that 400 μm pattern is large enough to be visible. In order to solve this paradox, the image distortion effect should be enhanced and it can be achieved on a mobile device even when the size of the cuboid is smaller than 400 μm.

On a mobile device, the gap between the display panel and the surface of the device is approximately 2 mm, as there are many structures such as touch panels, a cover glass, and optical films, over the display panel. When there is a gap of a certain size between privacy filters with micro-cuboid arrays and display panel, the effect of image distortion is enhanced. Figure 3 describes the concept of this gap effect in the privacy filter.

In Fig. 3(a), the observed character distance is increased as the privacy filter with micro-cuboid arrays moves away from the display. When the cuboid size is much smaller than gap $d$, the character distance is approximately equal to $2d \tan \theta$ where $d$ is the gap between the display and the privacy filter. If $d$ is 2 mm, the left character 'O' (①) is observed 4 mm away from the right character 'O' (②) to observer at an inclined view of 45°. Considering that 4 mm is comparable to the size of the character, this situation can lead to image distortion on a mobile device.

When cuboid (200 μm × 200 μm × 200 μm) arrays are applied to characters 4 mm in size, as shown in Fig. 3(b), the gap clearly influences the degree of image distortion. As $d$ varies from 0 to 2 mm, the distance between the duplicated characters is increased. This causes different characters to overlap and hinders the recognition of these characters. Further, the viewing angle can be adjusted by the cuboid thickness. Figure 3(c) describes the effect of the cuboid thickness on the viewing angle. As the thickness of the cuboid increases, the duplicated characters have more visibility; as a result, the viewing angle becomes narrower.

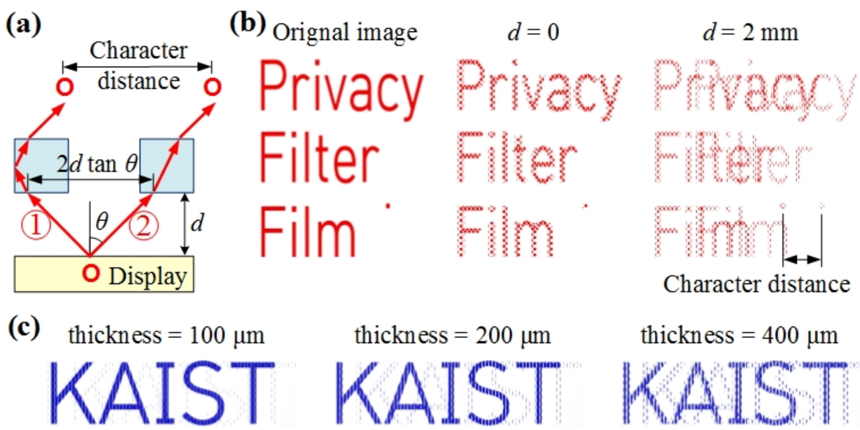


Fig. 3. Concept of the gap effect in the privacy filter with the micro-cuboid arrays. (a) Observed character distance is affected by the gap $d$ between the display and the privacy filter. (b) Simulated images of the gap effect from an inclined view (45°). The characters are duplicated and overlapped when $d$ is 2 mm. (c) Simulated images describing the effect of the cuboid thickness from an inclined view (15°).

### 3. Results and discussion

Figure 4(a) depicts the fabrication process of the PDMS privacy filter with micro-cuboid arrays. The SU-8 100 mold for the privacy filter is fabricated by UV lithography. After that, PDMS is poured into the SU-8 mold and later released from the mold, transcribing the pattern. Figure 4(b) shows a top view and cross-sectional view of the fabricated PDMS privacy filter, which shows high-transparency.

In order to test the effect of the fabricated privacy filter with the micro-cuboids, the privacy filter is set onto a paper printed with characters 2~4 mm in size. As shown in Fig. 4(c), by employing cuboid arrays of 400 μm, the characters are scarcely recognizable due to the image distortion, even without a gap in the inclined view. However, the 400 μm size has an adverse effect on the readability considering that the array size is large enough to be recognized by the human eye; thus, it is too thick to be used.

In Fig. 4(d), the 200 μm micro-cuboid arrays of the privacy filter are comfortable for the eyes in the normal direction, as the edge of a 200 μm micro-cuboid is small enough to be invisible. In an inclined direction, the effect of image distortion is not significant such that the characters become foggy but are still readable. Figure 4(e) depicts the 200 μm micro-cuboid arrays of the privacy filter on a 1 mm thick glass substrate, which creates a 1 mm gap *d*, between the characters and the privacy filter with the micro-cuboid arrays. Consequently, the duplicated characters, which in turn causes different characters to be overlapped in an inclined direction, successfully conceal the information. In contrast, the characters are not distorted in the normal direction.

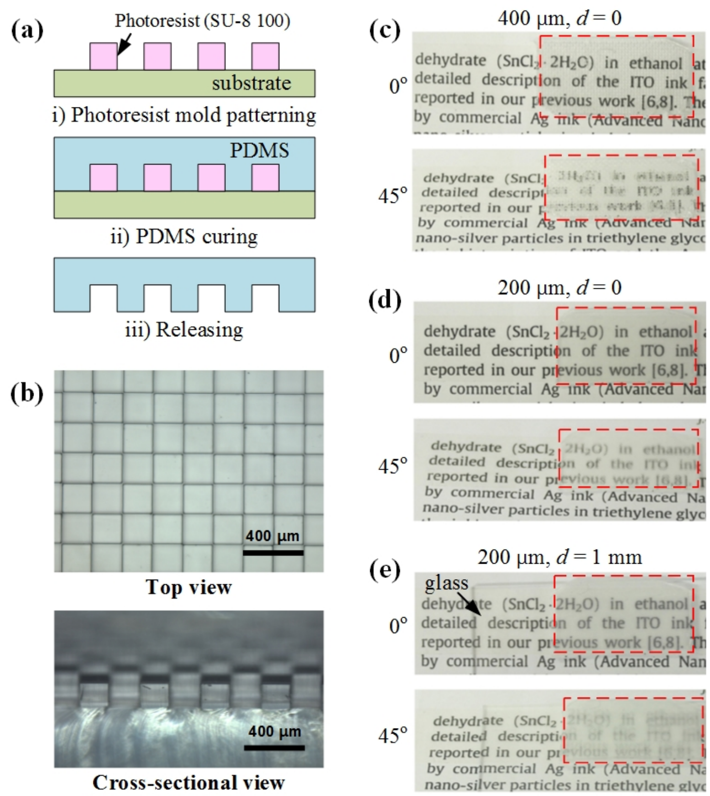


Fig. 4. (a) Fabrication process of the PDMS privacy filter with the micro-cuboid arrays. (b) Top view and cross-sectional view of the fabricated PDMS privacy filter. (c)-(e) Effects of the cuboid size and gap *d*, on the privacy filter: (c) 400 μm cuboid when $d = 0$, (d) 200 μm cuboid when $d = 0$, and (e) 200 μm cuboid when $d = 1$ mm.

In Fig. 5, the PDMS privacy filter with the 100 μm × 100 μm × 200 μm cuboids is fabricated and attached onto a mobile device (a LG smart phone, LG-F240, Korea). Figure 5(a) shows the brightness with respect to the view angle of light source and source with PDMS privacy filter using a spectroradiometer (CS-2000, Konica Minolta, Inc.). The reduction in brightness is not significant when attaching PDMS privacy filter on light source. Also, the transparency of the PDMS privacy filters in normal direction was measured using an

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UV spectrophotometer (V-530, JASCO co.) as shown in Fig. 5(b). The transmittance of the PDMS filter ii) is 88% which is higher than those of commercial filters iii) and iv). The text under the privacy filter is observed from three different directions [Fig. 5(c)]. In the normal direction <001>, a clear image is observed and the cuboid arrays are not recognizable, as shown in Fig. 5(d). Figure 5(e) depicts the observed image at a 45° tilted view from the y-axis <011>, showing how the characters become foggy and duplicated. In <111> direction, the characters are replicated into several directions and are impossible to recognize [Fig. 5(f)]. These experimental results show that the proposed privacy filter with the micro-cuboid arrays is sufficiently effective for the protection of personal information without the use of any opaque materials. Further, considering that these distortion effect are caused by the change of the light ray path at given incidence angle, it is possible to prevent the information regardless of polarization.

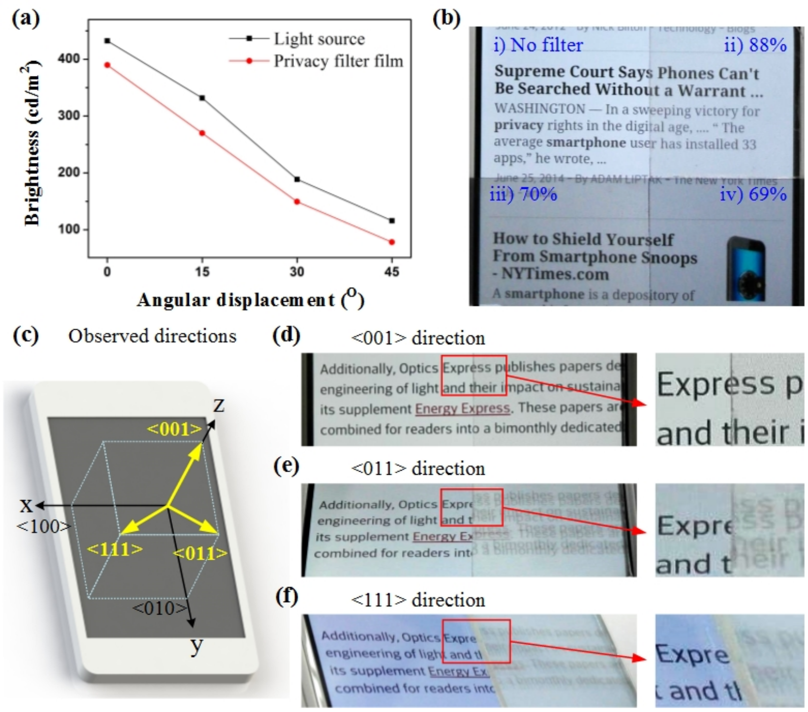


Fig. 5. The PDMS privacy filter with 100 μm × 100 μm × 200 μm cuboid arrays attached onto a mobile device. (a) Brightness change depending on view angles. (b) Transparency difference between PDMS privacy filter ii) and commercial privacy filters iii) and iv). (c) Three different observed directions. (d)-(e) Experimental results with the PDMS privacy filter obtained in the three observed directions.

## 4. Summary

In summary, we proposed highly transparent privacy filter film with micro-cuboid arrays to achieve good image distortion. The privacy filter does not require any opaque materials and therefore provides maximum transparency, yielding a myriad of benefits on mobile devices given their limited battery capacity. In addition, these privacy filters with micro-cuboid arrays are suitable for commercialization and the roll-to-roll process using thermosetting resin. This facilitates the mass production of these devices.


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