High-Chroma Visual Cryptography Using Interference Color of High-Order Retarder Films

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Visual cryptography can be used as a method of sharing a secret image through several encrypted images. Conventional visual cryptography can display only monochrome images. We have developed a high-chroma color visual encryption technique using the interference color of high-order retarder films. The encrypted films are composed of a polarizing film and retarder films. The retarder films exhibit interference color when they are sandwiched between two polarizing films. We propose a stacking technique for displaying high-chroma interference color images. A prototype visual cryptography device using high-chroma interference color is developed.

Keywords: visual cryptography, information security, interference color, retarder film

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1. Introduction

Various optical cryptography schemes and devices have been proposed for information security.[1-7] Visual cryptography can be used as a method of sharing a secret image through several encrypted images. The basic algorithm of visual cryptography was reported by Naor and Shamir[8] and Kafri and Keren.[9] This algorithm is considered to be very effective because no information about the secret image leaks from each separated key image. In conventional visual cryptography, each key image (share) is a random distribution of black and white subpixels. When shares are copied on transparencies, the secret image can be observed by stacking them. Many types of visual cryptography have been proposed.[8-19] Conventional visual cryptography reduces the quality of decoded images because the encryption is based on spatial coding that requires multiple subpixels to modulate the light intensity. A polarization encoding technique solves this problem. This encoding technique enables the encryption of each pixel in a secret image into a corresponding single pixel in shares.[1-3, 12] A simple polarization encoding technique without an optical system was reported by Imagawa et al.[13] A visual encryption device using high-order retarder films was also reported by Kowa et al.[14] These techniques enable the display of only a binary image. In conventional visual cryptography, the image is encoded into a black and white binary pattern, and the decoded image can only be displayed as a black and white binary image. Improved visual cryptography for gray-level images was reported by Blundo et al.[15] Visual cryptography for color images has also been reported.[16-19] A color visual cryptography technique is useful for various applications, but multiple color subpixels are needed. For example, to represent color images with two shares, each pixel must be composed of at least one red, one green, and one blue subpixel. To represent black, the minimum number of subpixels is six, where each pixel is composed of one red, one green, one blue, and three black subpixels.[16] These color subpixels reduce the quality of secret images. This is a problem of conventional color visual cryptography. We have already reported color visual cryptography using interference color.[20] Our encoding technique enables the encryption of each pixel in a secret image into a corresponding single pixel in shares. We can display red, green, and blue in a single pixel in shares. Therefore, the image quality is not reduced by stacking shares, which is an advantage of our proposed system. In contrast with other methods, our system involves no absorption of color ink or color filters, and we use the interference color of high-order retarder films. Interference color is an important source of information for the microscopic observation of birefringent materials.[21] Interference color is also used as educational tools.[22-23]

A weak point of our previous visual cryptography method reported in Ref. 21 is the quality of the color. High-chroma color cannot be displayed using interference color. To solve this problem, we propose a technique involving the stacking of retarder films. Our system is composed of up to four transparent retarder films and two polarizers. Each color is controlled by the phase retardation and setting angle of the retarder films. We describe conventional and extended high-chroma interference color using polarization films in Sect. 2. In Sect. 3, we describe experiments on high-chroma displays using interference color. In Sect. 4, we present the proposed method of high-chroma visual cryptography using interference color.

2. Principles of High-Chroma Display Using Interference Color

In this section, the principles of high-chroma indication using interference color are described. Figure 1 shows a example of a simple design algorithm for high-chroma indication using interference color. Figure 1(a) shows the conventional optical arrangement. The angle between the transmission axis of a polarizer and the retarder axis of a retarder film is 45° or 135° because the maximum transmittance is obtained at these angles. Figure 1(b) shows the proposed optical arrangement. The angle between the transmission axis of a polarizer and the retarder axis of a retarder film can be varied, and up to four retarder films are stacked. Using this proposed setup, we can display a high-chroma image.

Visible color is completely specified by the trichromatic coordinates *X*, *Y*, and *Z* adopted by the Commission Internationale de l'Éclairage (CIE).[24,25] When the birefringence dispersion is negligible, the tristimulus *X*, *Y*, and *Z* values of a specific interference color obtained using crossed polarizers are given by

$$X = K\int_{380}^{780} S(\lambda)\bar{x}(\lambda)\sin^2\left(\frac{\pi R}{\lambda}\right)d\lambda \quad , (1)$$

$$Y = K\int_{380}^{780} S(\lambda)\bar{y}(\lambda)\sin^2\left(\frac{\pi R}{\lambda}\right)d\lambda \quad , (2)$$

$$Z = K\int_{380}^{780} S(\lambda)\bar{z}(\lambda)\sin^2\left(\frac{\pi R}{\lambda}\right)d\lambda \quad , (3)$$

$$K = \frac{100}{\int_{380}^{780} S(\lambda)\bar{y}(\lambda)d\lambda}, \quad (4)$$

where $S(\lambda)$ is the spectral distribution of the illuminant, $\bar{x}$, $\bar{y}$, and $\bar{z}$ are the tristimulus values of the standard observer, *R* is the retardation, and λ is the wavelength. The *XYZ* colorimetric system is used to express all visible colors using only positive values, and the *Y* value is the luminance. In the *XYZ* colorimetric system, it is difficult to determine the relationship between *X*, *Y*, and *Z* values and color. The *xyY* colorimetric system is useful for determining the color directly from the *x*, *y*, and *Y* values. The *x* and *y* values are defined by

$$x = \frac{X}{X + Y + Z}, \quad (5)$$

$$y = \frac{Y}{X + Y + Z}. \quad (6)$$

Figure 2(a) shows the calculated chromaticity curves of the interference color from the CIE standard illumination D65 using the conventional method shown in Fig. 1(a). The phase retardation of the retarder films is calculated from 1 to 2000 nm in intervals of 1 nm. The displayed chroma saturation of the interference color is low, but various colors can be displayed by changing the phase retardation of the retarder films. λ/4, λ/2, and λ retarder films are commercially available. The black squares in Fig. 2(a) show the calculated interference color, which can be displayed using a combination of commercially available retarder films. Only a limited range of colors can be displayed using commercially available retarder films. To solve this problem, we propose changing the setting angle of the retarder films. Figures 2(b), 2(c), and 2(d) show the calculated chromaticity curves of the interference color using the proposed method shown in Fig. 1(b).

To obtain the chromaticity curves in Fig. 2(b), two retarder films (one λ/4 retarder film and one λ retarder film) are placed between crossed polarizers. The calculated angle between the transmission axis of a polarizer and the retarder axis of a retarder film is varied from 0° to 180° in intervals of 1°; thus, there are 180 x 180 combinations in the calculation. The displayed chroma of the interference color is rather low, but various colors can be displayed by changing the setting angle of the retarder films. The displayed chroma of the interference color can be improved by increasing the number of stacking films. Three retarder films are used in the calculation shown in Fig. 2(c). The stacking order is a λ retarder film, a λ/4 retarder film, and a λ retarder film. The calculated angle between the transmission axis of a polarizer and the retarder axis of a retarder film is from 0° to 180° in intervals of 1°. Four retarder films are used to obtain the curve shown in Fig. 2(d). The stacking order is a λ retarder film, a λ retarder film, a λ/4 retarder film, and a λ retarder film. The calculated angle between the transmission axis of a polarizer and the retarder axis of a retarder film is from 0° to 180° in intervals of 2°. In this way, we can cover a larger area of the xy color chart by increasing the total number of retarder films. The displayed chroma of the interference color is high compared with that obtained by the conventional method. Other combinations of stacking retarder films are possible. We can cover other areas of the xy color chart by changing the stacking of the retarder films or the number of retarder films.

3. Experiment on High-Chroma Indication Using Interference Color

In this section, experimental results for the interference color using conventional method and proposed method are shown. In the conventional method, the displayed chroma of the interference color is low. In particular, it is difficult to display red using the conventional method. Figures 3(a) and 3(b) show optical setups for displaying red using the conventional method and the proposed method. λ retarder films and λ/4 retarder films are used in this experiment. The retardations of the λ retarder film and λ/4 retarder film used in these experiments are 570 nm and 140 nm, respectively. In the conventional method, one λ retarder film and one λ/4 retarder film are used. The slow axes of the retarder films are set to 45° and 135° and the total retardation is 430 nm.

Figure 4(a) shows the transmission spectrum obtained using the conventional method. The transmission spectrum is wide and the displayed chroma of the interference color is low. In the proposed method, two λ retarder films and one λ/4 retarder film are used. The slow axes of the retarder films are set to 122°, 83°, and 122°, which are one set of suitable angles for displaying red according to a theoretical calculation. Figure 4(b) shows the transmission spectrum obtained using the conventional method. The transmission spectrum is narrower than that in Fig. 4(a) and the displayed chroma of the interference color is high. Figure 5(a) shows examples of optical alignments for displaying various colors, and Fig. 5(b) shows the displayed interference colors. We can display black, white, and grayscale monotone images. We can also display red, green, blue, cyan, magenta, and yellow with high chroma. In this way, we can calculate suitable angles of the retarder films for displaying many other colors.

4. Proposed Method of Visual Cryptography Using Interference Color

Various colors can be displayed by changing the setting angles of the retarder films, and the colors can be changed by increasing or decreasing the phase retardations. In this section, we show the proposed method of high-chroma visual cryptography using interference color. Figure 6 shows some possible combinations of key images in visual cryptography using interference color. We consider that one pixel of a secret image is shared through two key images (key images 1 and 2). In this example, three retarder films are stacked as shown in Fig 6(1). Various combinations of retarder films can be used to design key images. Three retarder films are shared through two key images in Figs. 6(2) and 6(3). In this case, one key image consists of zero to three retarder films. We can stack other dummy films such as in Figs. 6(4) and 6(5). In this case, two dummy retarder films are stacked on key images 1 and 2 by placing the films in orthogonal directions. In this way, the displayed color of each key image can be changed. Color information is not leaked from either key image. The retardations of the two dummy retarder films are compensated when the key images are overlaid.

Next, we designed a prototype multicolor visual cryptography device using interference color. A secret image of 10 x 10 pixels with a pixel size of 12 x 12 mm^2 was composed. Retarder films were cut using a cutting plotter. In the device, retarder films of each pixel are shared through two key images (key images 1 and 2). Dummy retarder films are also stacked on key image 1 and 2. Figures 7(a) and 7(b) show the interference colors of key images 1 and 2 with crossed polarizers. A KLV-7000 (Hakuba corp.) white backlight was used to view the image. A random pattern of colors was observed. No information was leaked from either key image. Figure 7(c) shows the result of incorrectly overlaying key images 1 and 2 with crossed polarizers. In this case, the direction of the key image was not correct, and the correct image was not observed. When a slight shift between the two images existed, we observed an image of random colors. Figure 7(d) shows the result of correctly overlaying key images 1 and 2 with crossed polarizers. High-chroma visual cryptography was thus successfully demonstrated using interference color.

5. Conclusions

We have produced a high chroma color visual encryption technique using the interference color of high-order retarder films. We calculated the interference color for the conventional method and the proposed method. A prototype high-chroma visual cryptography device using interference color was developed, in which no special optical systems are required to observe portable encrypted images. Color filters and color subpixels are also not needed; thus, the encoding technique proposed in this study enables the encryption of each pixel in a secret image into a corresponding single pixel in shares. This technique is very simple and can be applied in, for example, security, entertainment, and educational use.

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Figure Captions

Fig. 1. Optical arrangement of polarizers and retarder films. (a) Conventional method and (b) proposed method.

Fig. 2. Calculated chromaticity curves of interference color from CIE standard illumination D65. (a) Conventional method, (b) proposed method (two retarder films). (c) proposed method (three retarder films), and (d) proposed method (four retarder films).

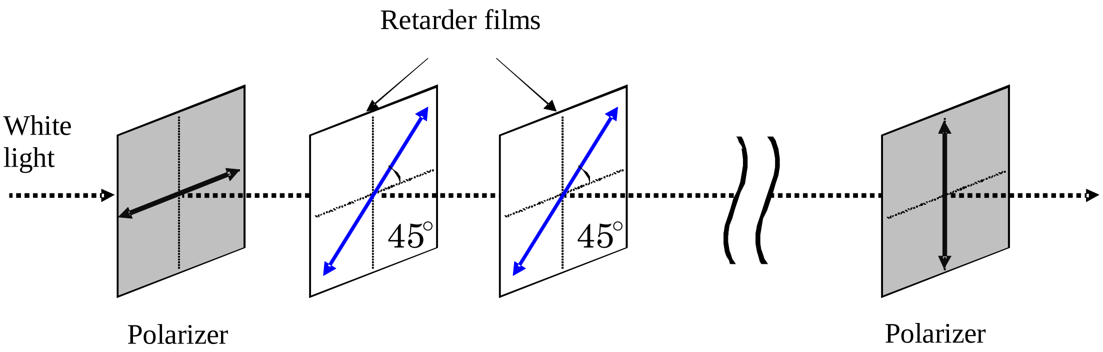
Fig. 3. Optical arrangement of polarizers and retarder films for displaying red. (a) Conventional method and (b) proposed method.

Fig. 4. Transmission spectrum of interference color. (a) Conventional method and (b) proposed method.

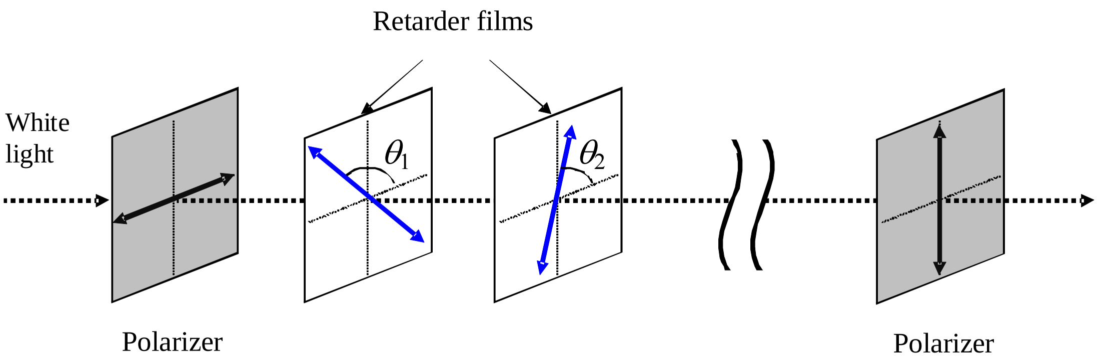
Fig. 5. Example of interference colors. (a) Optical alignments and (b) displayed colors.

Fig. 6. Proposed method of visual cryptography.

Fig. 7. Proposed high-chroma multicolor visual cryptography using interference color. (a) Key image 1, (b) key image 2, (c) incorrectly decoded image, and (d) correctly decoded image.

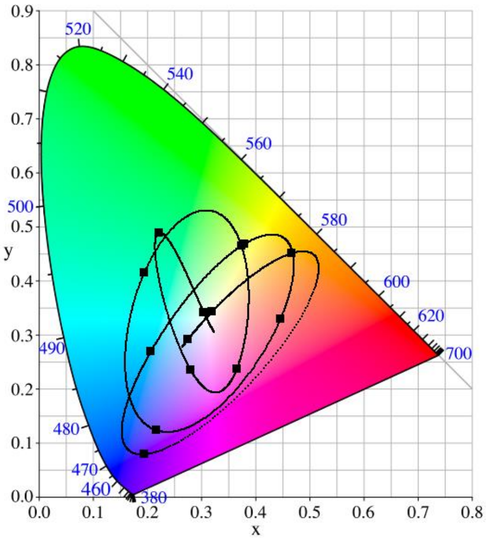


(a) Conventional method

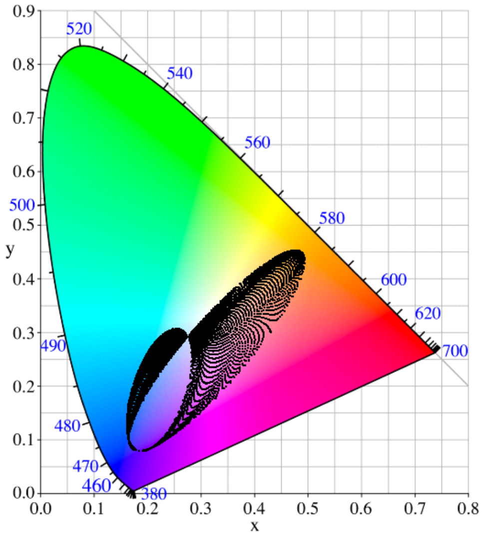


(b) Proposed method

Figure 1

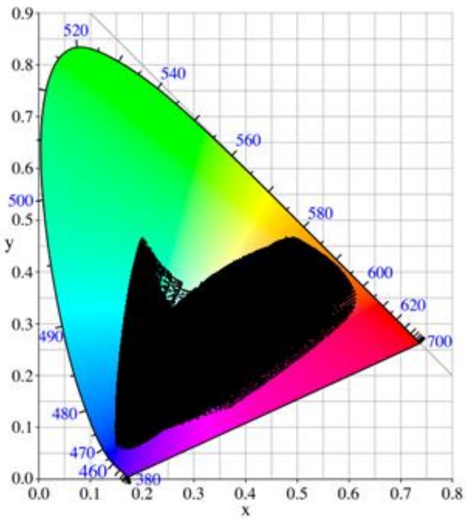


(a) Conventional method



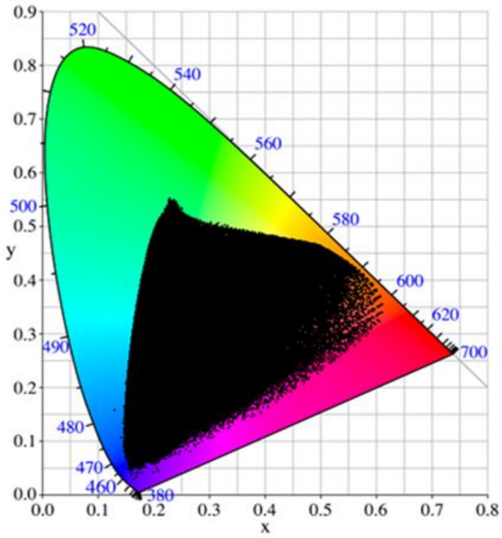
(b) Proposed method

(two retarder films)



(c) Proposed method

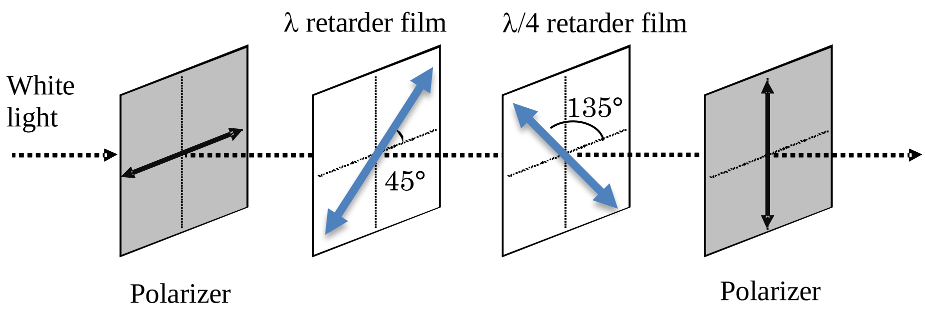
(three retarder films)



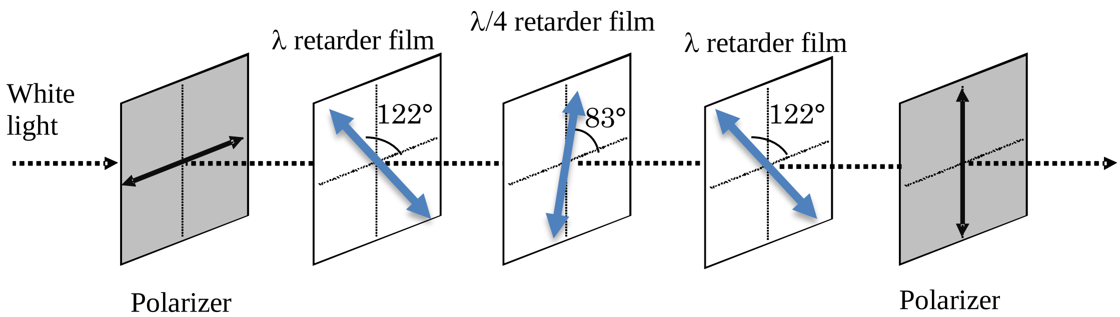
(d) Proposed method

(four retarder films)

Figure 2

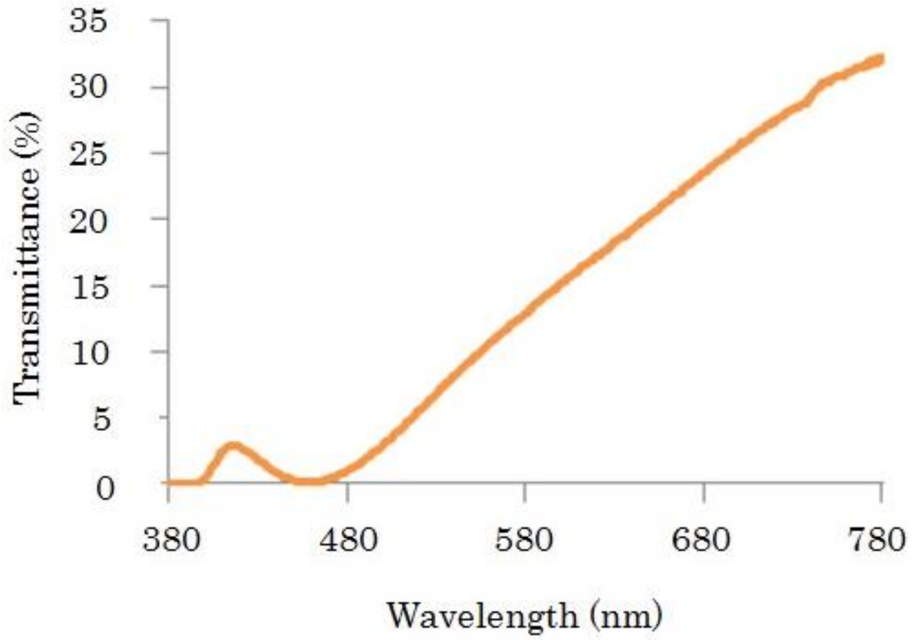


(a) Conventional method

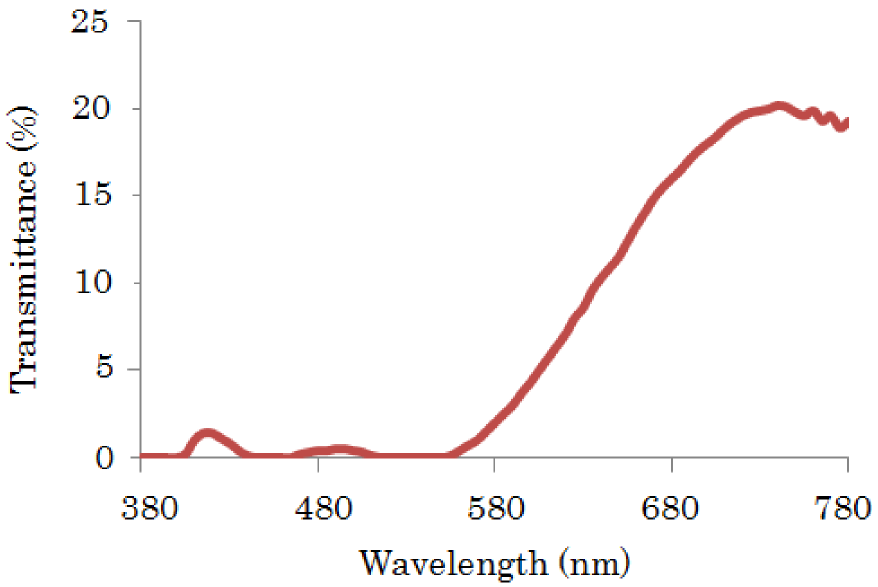


(b) Proposed method

Figure 3

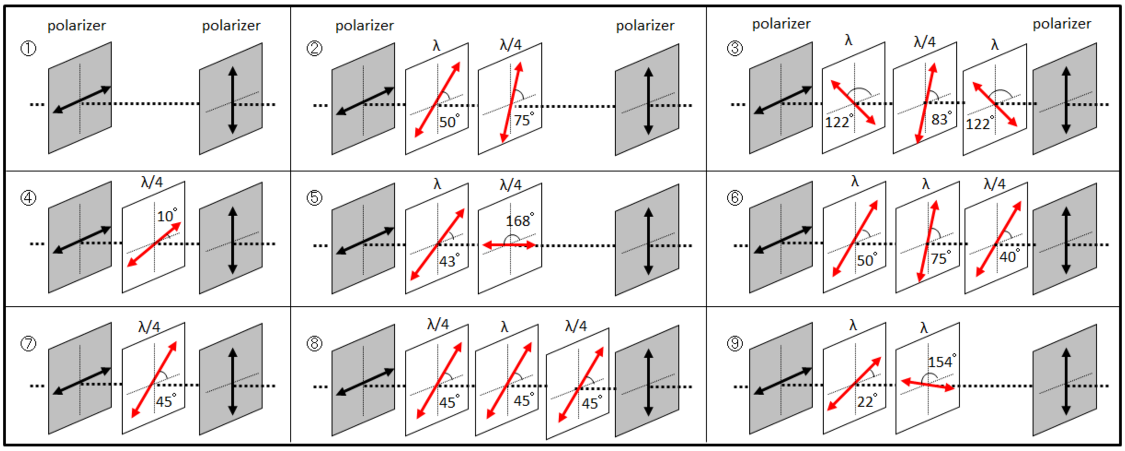


(a) Conventional method

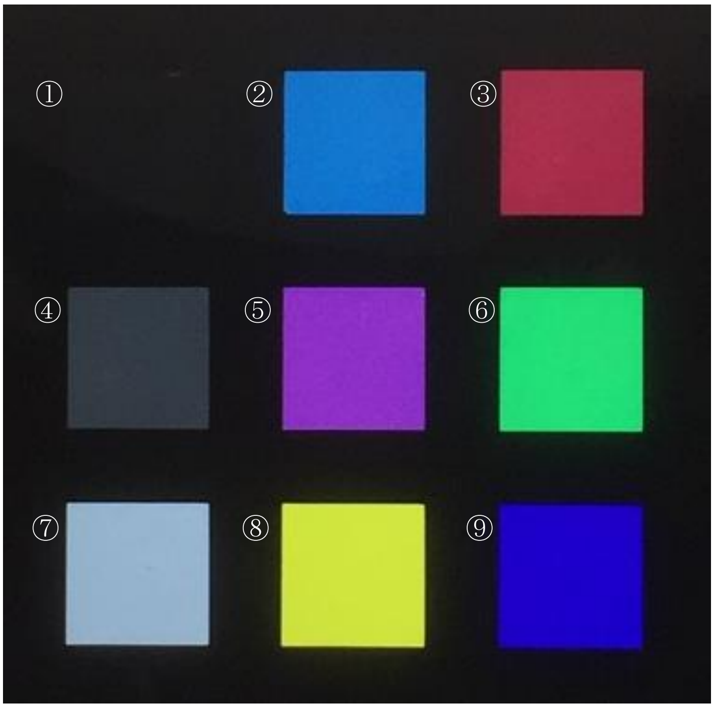


(b) Proposed method

Figure 4

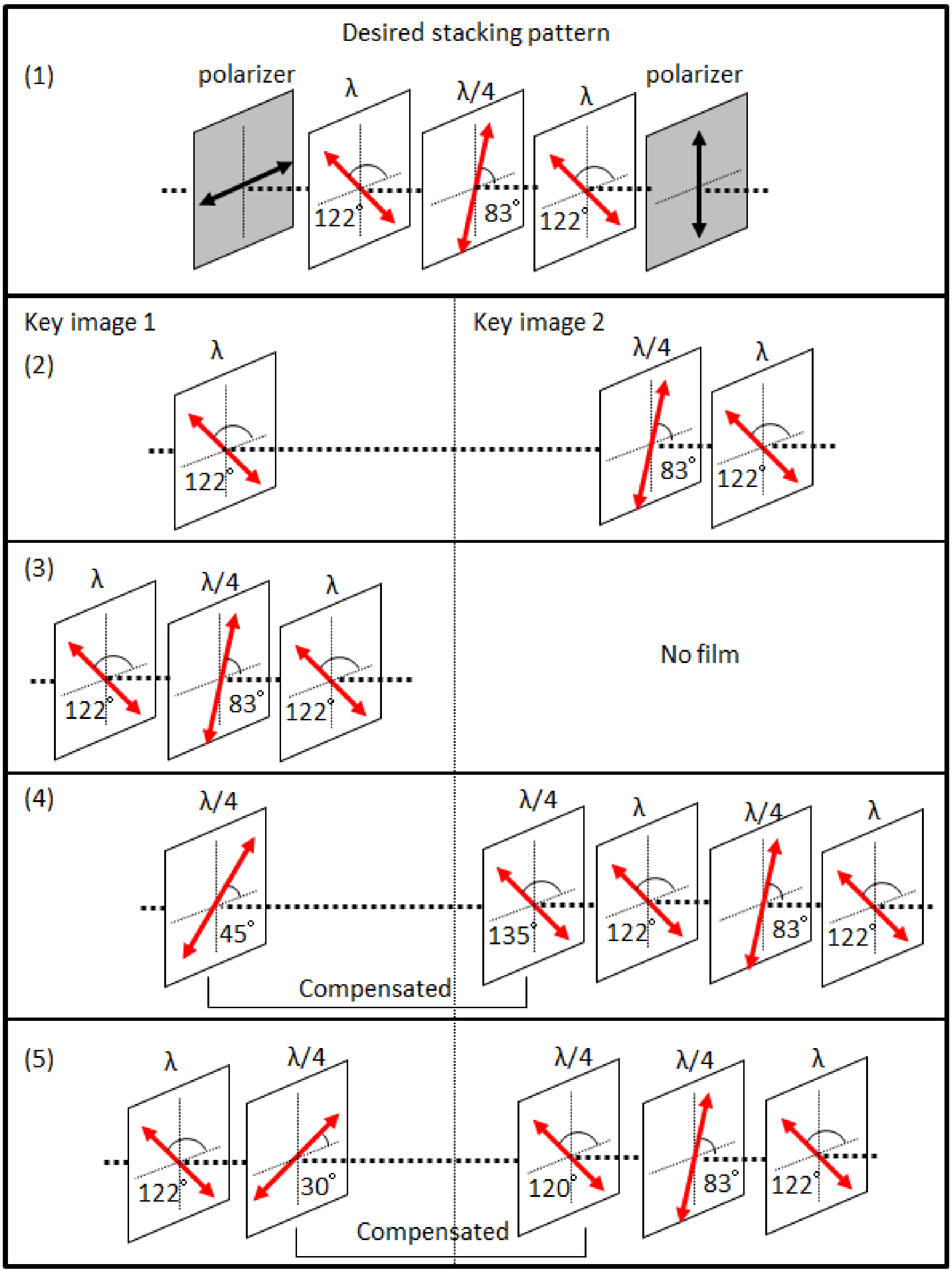


(a) Optical alignments



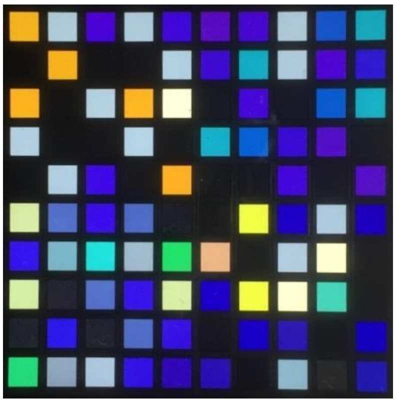
(b) Displayed colors

Figure 5

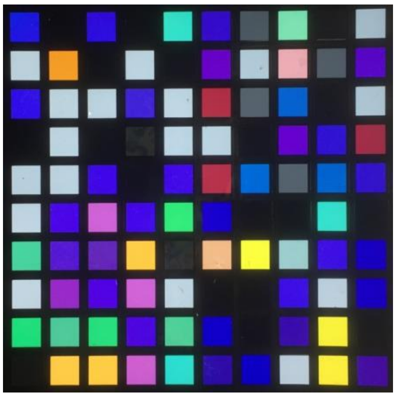


Desired stacking pattern
(1)
polarizer
λ
λ/4
λ
polarizer
122°
83°
122°
Key image 1
(2)
λ
122°
Key image 2
λ/4
λ
83°
122°
(3)
λ
λ/4
λ
122°
83°
122°
No film
(4)
λ/4
45°
Compensated
λ/4
λ
λ/4
λ
135°
122°
83°
122°
(5)
λ
λ/4
122°
30°
Compensated
λ/4
λ/4
λ
120°
83°
122°

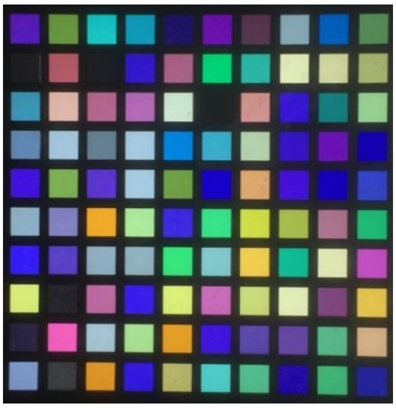
Figure 6



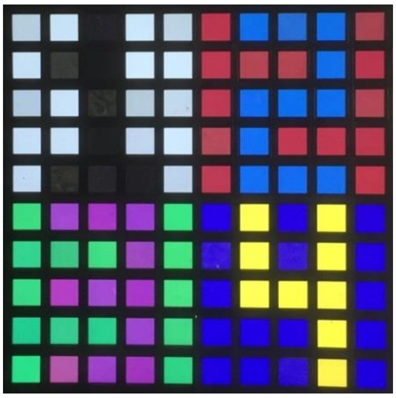
(a) Key image 1



(b) Key image 2



(c) Incorrectly decoded image



(d) Correctly decoded image

Figure 7