Optical color image encryption by wavelength multiplexing and lensless Fresnel transform holograms

Linfei Chen and Daomu Zhao

Department of Physics, Zhejiang University, Hangzhou 310027, China
zhaodaomu@yahoo.com

Abstract: We propose what we believe is a new method for color image encryption by use of wavelength multiplexing based on lensless Fresnel transform holograms. An image is separated into three channels: red, green, and blue, and each channel is independently encrypted. The system parameters of Fresnel transforms and random phase masks in each channel are keys in image encryption and decryption. An optical color image coding configuration with multichannel implementation and an optoelectronic color image encryption architecture with single-channel implementation are presented. The keys can be added by iteratively employing the Fresnel transforms. Computer simulations are given to prove the possibility of the proposed idea.

OCIS codes: (070.4560) Optical data processing; (100.2000) Digital image processing; (090.0090) Holography.

References and links

1. P. Refregier and B. Javidi, "Optical image encryption based on input plane and Fourier plane random encoding," Opt. Lett. **20,** 767-769 (1995).
2. B. Javidi, "Security information with optical technology," Phys. Today **50,** 27-32 (1997).
3. G. Unnikrishnan, J. Joseph, and K. Singh, "Optical encryption by double-random phase encoding in the fractional Fourier domain," Opt. Lett. **25,** 887-889 (2000).
4. G. Situ and J. Zhang, "Double random-phase encoding in the Fresnel domain," Opt. Lett. **29,** 1584-1586 (2004).
5. B. Hennelly and J. T. Sheridan, "Optical image encryption by random shifting in fractional Fourier domains," Opt. Lett. **28,** 269-271 (2003).
6. E. Tajahuerce, O. Matoba, S. C. Verrall, and B. Javidi, "Optoeletronic information encryption with phase-shifting interferometry," Appl. Opt. **39,** 2313-2320 (2000).
7. S. T. Liu, Q. L. Mi, and B. H. Zhu, "Optical image encryption with multistage and multichannel fractional Fourier-domain filtering," Opt. Lett. **26,** 1242-1244 (2001).
8. B. Javidi and T. Nomura, "Securing information by use of digital holography," Opt. Lett. **25,** 28-30 (2000).
9. X. Peng, L. F. Yu, and L. L. Cai, "Double-lock for image encryption with virtual optical wavelength," Opt. Exp. **10,** 41-45(2002).
10. N. K. Nishchal, J. Joseph, and K. Singh, "Securing information using fractional Fourier transform in digital holography," Opt. Commun. **235,** 253-259 (2004).
11. X. G. Wang, D. M. Zhao, F. Jing, and X. F. Wei, "Information synthesis (complex amplitude addition and subtraction) and encryption with digital holography and virtual optics," Opt. Exp. **14,** 1476-1486 (2006).
12. H. Kim, D. H. Kim, and Y. H. Lee, "Encryption of digital hologram of 3-D object by virtual optics," Opt. Exp. **12**, 4912-4921 (2004).
13. X. G. Wang, D. M. Zhao, and L. F. Chen, "Image encryption based on extended fractional Fourier transform and digital holography technique," Opt. Commun. **260,** 449-453 (2006).
14. L. F. Chen and D. M. Zhao, "Optical image encryption based on fractional wavelet transform," Opt. Commun. **254,** 361-367 (2005).
15. Y. Zhang, C. H. Zheng, and N. Tanno, "Optical encryption based on iterative fractional Fourier transform," Opt. Commun. **202,** 277-285 (2002).
16. G. H. Situ and J. J. Zhang, "Multiple-image encryption by wavelength multiplexing," Opt. Lett. **30,** 1306-1308 (2005).

#72115 - $15.00 USD Received 19 June 2006; revised 18 August 2006; accepted 21 August 2006

17. L. F. Chen and D. M. Zhao, "Optical image addition and encryption by multi-exposure based on fractional Fourier transform hologram," Chin. Phys. Lett. **23,** 603-606 (2006).
18. S. Q. Zhang and M. A. Karim, "Color image encryption using double random phase encoding," Microwave Opt. Technol. Lett. **21,** 318-323 (1999).
19. J. Nicolas, C. Iemmi, J. Compos, and M. J. Yzuel, "Optical encoding of color three-dimensional correlation," Opt. Commun. **209,** 35-43 (2002).
20. S. Ledesma, C. Iemmi, M. Villarreal, and J. Compos, "Multichannel correlation by color multiplexing," Opt. Commun. **166,** 173-180 (1999).
21. W. M. Jin, L. H. Ma, and C. J. Yan, "Real color fractional Fourier transform holograms," Opt. Commun. **259,** 513-516 (2006).

1. Introduction

Since Refregier and Javidi [1] proposed the double random phase encryption method for the first time in 1995, more and more people have been attracted in this domain and a number of optical image encryption techniques have been proposed for its interesting and meaningful in practical applications [2-17]. In a double random encoding system, the image is encoded to be a white noise picture with two random phase plates, which are displayed respectively at the input plane and Fourier plane. In 2000, Unnikrishnan et al. [3] presented a new method and suggested placing the second random phase plate at the fractional plane rather than the Fourier plane, then the encryption technique based on fractional Fourier transform was proposed. Furthermore, in 2004 Situ and Zhang [4] employed a lensless double random encoding system by Fresnel transforms. Except for double random phase masks, the system parameters are also their important keys in decoding in the last two methods. Meanwhile, there are many other good techniques for optical image encryption, such as encryption with digital holography [8-13] or joint transform correlators, etc. However, in these methods, the images are illuminated by monochromatic light, and the reconstructed images would lose their color information. In many cases, we need the color information, not only for its beautiful in vision but also for its useful in practical applications. In 1999, Zhang and Karim [18] introduced a new method for color image encryption based on Fourier transform, but after that, to our knowledge, no other optical methods have been proposed or published in this area, though color processing method is often used in color pattern recognition [19, 20]. Wavelength multiplexing method was proposed by Situ and Zhang in 2004 [16] for multiple image encryption, and a real color fractional Fourier transform has been presented recently by Jin et al. [21]. In this paper, we introduce a new optical color image encryption method by wavelength multiplexing based on lensless Fresnel transform holograms and double random phase encryption. A pure optical architecture with multichannel implementation and an optoelectronic realization with single channel method are designed in this paper, and an iterative color image coding method is presented to increase the security. The first optical setup we proposed can realize the encryption or decryption process in real time and does not rely on electronics devices, what are its virtues compared to the previous method in Ref. [18]. And the second configuration is much simpler and easier to carry out, but it is not a pure optical realization and relies on some electronics devices (CCD, Computer and SLM), and it may not be implemented in real time. Both the optical and optoelectronic architectures are realized based on lensless Fresnel transform holograms, the system parameters are additional keys compared to the previous method, which indicates that our method would improve the security and has potential usage both in optical and wireless color image coding.

2. Double random encryption and Fresnel transform holograms

Here we first discuss the theoretical background of the proposed idea. The double random phase coding method in Fresnel domain or with digital Fresnel transform hologram techniques are widely used in image encryption. The encoding process in Fresnel domain can be written as

$$g(x_2, y_2) = \mathrm{FsT}\left\{\mathrm{FsT}\left[f(x, y)P(x, y); z_1 \right] \times K(x_1, y_1); z_2 \right\}, \tag{1}$$

and the decrypting process is expressed as follows

$$f'(x,y)=\mathrm{FsT}\{\mathrm{FsT}[g^*(x_2,y_2);z_2]\times K(x_1,y_1);z_1\}, \tag{2}$$

where

$$\mathrm{FsT}[f(x,y);z]=\frac{\exp(i2\pi z/\lambda)}{i\lambda z}\iint f(x,y)\exp\left\{\frac{i\pi}{\lambda z}\left[(x_1-x)^2+(y_1-y)^2\right]\right\}\mathrm{d}x\mathrm{d}y, \tag{3}$$

and

$$P(x,y)=\exp[2\pi i p(x,y)],\ K(x,y)=\exp[2\pi i k(x,y)]. \tag{4}$$

In the above equation $p(x,y)$ and $k(x,y)$ are two independent white sequences uniformly distributed on the interval [0, 1]. The double random phase masks are placed respectively at the input plane and Fresnel plane. The information at the output plane is recorded on a hologram halide by a reference beam. When the reference beam is a plane wave of uniform unitary amplitude, the holographic data is described as

$$\begin{aligned} u(x',y') &= |1+g(x_2,y_2)|^2 \\ &= 1+|g(x_2,y_2)|^2+g^*(x_2,y_2)+g(x_2,y_2). \end{aligned} \tag{5}$$

In decryption, the hologram halide is displayed at the input plane and the third term on the right-hand side of Eq. (5) can be used to recover the image at the output plane as described in Eq. (2).

In Eq. (3), the factor λ is the wavelength of an incident beam, which is a monochromatic beam that corresponds to a certain color with the wavelength. So the decryption image would also be a single color picture, and its real color information is lost, which is shown in Fig. 1.

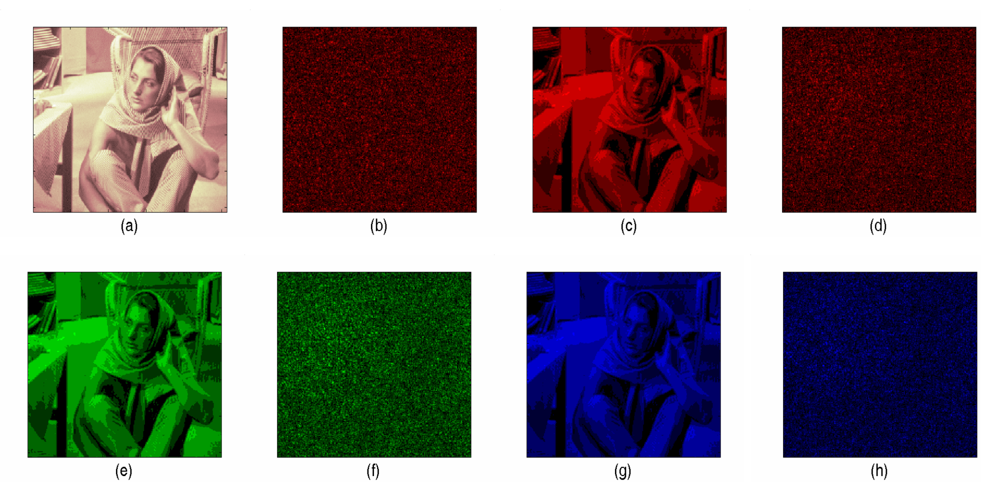

Fig. 1. Image encryption and decryption by single wavelength illumination. (a) Original image with 256×256 pixels; (b) encrypted image with red wavelength; (c) and (d) correct and incorrect decryption images with red wavelength; (e) and (f) correct and incorrect decoding images with green wavelength; (g) and (h) right and wrong decryption results with blue wavelength.

Figure 1(a) is an input real color image, the picture of a beautiful woman with 256×256 pixels. The actual size of the image and the phase masks in the simulation are 6 mm. Figure 1(b) shows an example of encrypted result with a red wavelength illumination such as 632.8nm, and Figs. 1(c) and 1(d) give its correct and incorrect decryption results respectively.

While Figs. 1(e) and 1(f) denote the right and wrong decryption images with green incident beam. Also, Figs. 1(g) and 1(h) are correct and incorrect results illuminated by blue wavelength. In all these decryption images, the real color information is lost and the images lose some of their beautiful characteristics.

3. Color image encryption based on Fresnel transform holograms

In a color image, each pixel is represented by three RGB values of its color, as shown in Fig. 2. The real color is the composition of three RGB values with certain proportions. Therefore, $f(x,y)$ can be decomposed into three components $R(x,y)$, $G(x,y)$ and $B(x,y)$, each component corresponds to one color (red, green or blue). To incorporate the color information, it is suggested by using a multichannel method to separate the image into red, green and blue three channels and each channel is to be independently encrypted. If the incident wavelength of each channel is close to the wavelength of basic color, the real color information can be recovered at the output plane in decryption.

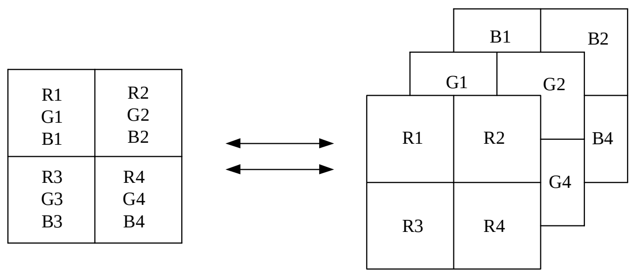

Fig. 2. Color image decomposition. R: Red; G: Green; B: Blue.

The security of information is the most important factor in image encryption technology. In order to improve the performance of security, we iteratively employ the Fresnel transform for several times and add the keys by this way. The encoding in one channel can be expressed as

$$\begin{aligned} g(x_n,y_n) = \iint\iint\cdots\iint & f(x,y)P(x,y)h(x_1,x;y_1,y;z_1) \\ & \times K_1(x_1,y_1)h(x_2,x_1;y_2,y_1;z_2)K_2(x_2,y_2)\ldots\ldots \\ & \times K_{n-1}(x_{n-1},y_{n-1})h(x_n,x_{n-1};y_n,y_{n-1};z_n)\mathrm{d}x\mathrm{d}x_1\ldots\mathrm{d}x_{n-1}\mathrm{d}y\mathrm{d}y_1\ldots\mathrm{d}y_{n-1} \end{aligned} \quad , \tag{6}$$

where

$$h(x_n,x_{n-1};y_n,y_{n-1};z_n) = \frac{\exp(i2\pi z_n/\lambda)}{i\lambda z_n}\exp\left\{\frac{i\pi}{\lambda z_n}\left[(x_n-x_{n-1})^2+(y_n-y_{n-1})^2\right]\right\}, \tag{7}$$

and its decoding process is written as

$$\begin{aligned} f'(x,y) = \iint\iint\cdots\iint & g^*(x_n,y_n)h(x_{n-1},x_n;y_{n-1},y_n;z_n) \\ & \times K_{n-1}(x_{n-1},y_{n-1})\ldots\ldots h(x_1,x_2;y_1,y_2;z_2)K_1(x_1,y_1), \\ & \times h(x,x_1;y,y_1;z_1)\mathrm{d}x_n\mathrm{d}x_{n-1}\ldots\mathrm{d}x_1\mathrm{d}y_n\mathrm{d}y_{n-1}\ldots\mathrm{d}y_1 \end{aligned} \tag{8}$$

where P, K_1, K_2 ,K_{n-1}; z_1, z_2, z_n are all keys in decoding, the number of the keys increase rapidly, and it is impossible for an unauthorized person to get the information without correct keys.

On the basis of the double random phase encryption technique and Fresnel transform holograms, an optical scheme of color image encryption is proposed with wavelength

#72115 - $15.00 USD Received 19 June 2006; revised 18 August 2006; accepted 21 August 2006

multiplexing as illustrated in Fig. 3. The red, green and blue color components are obtained by three lasers of different wavelengths, which must be close to the wavelengths of basic RGB color. In the computer, the wavelengths of basic RGB color are 700nm, 546.1nm and 435.8nm respectively. Ms are dichroic mirrors, which can separate the three wavelengths and let them go to different ways. The dichroic mirrors at different positions should be specifically selected, for example, M_4 should be chosen with high reflection index for red wavelengths and high transmission index for other wavelengths. I means the input plane, where the original color image is displayed. P and Ks are random phase masks, which are placed respectively at the input plane and Fresnel domains. Each color component passes through distances z_1, z_2, z_n, where random phase masks K_1, K_2, K_n, placed at corresponding Fresnel planes, it follows the basic theory of Fresnel transform and double random phase encryption method, which is mentioned in above section. All these three components join together, written on a hologram halide (H) with three corresponding reference beams. This pure optical setup can realize the encryption in real time but does not rely on electronics devices (such as CCD, Computer or SLM, etc.).

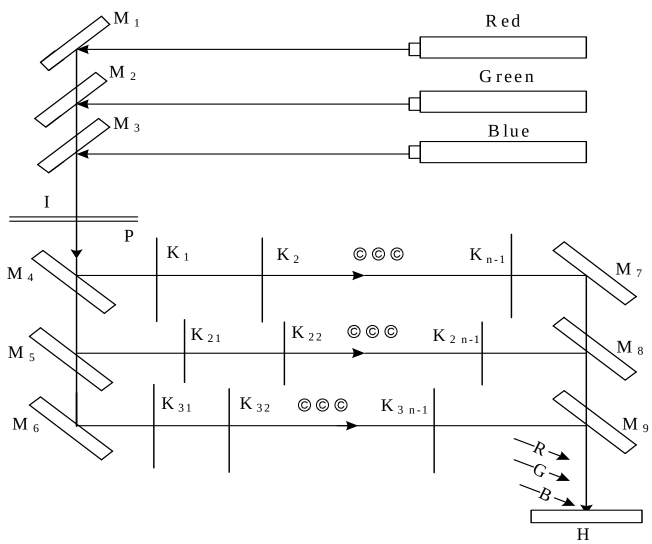

Fig. 3. Schematic of optical color image encoding implementation. Ms: dichroic mirrors; I: Input plane; P and Ks: random phase masks; H: hologram halide.

Another optoelectronic realization of color image encryption is presented in Fig. 4. The information, encrypted with different wavelengths and keys, is recorded by a CCD camera one by one at the output plane, then the three homochromatic images are changed to be a color encrypted image in the computer. The encoding processes are the same as above method. This configuration has some better virtues than the first optical implementation, such as, it is much simpler and easier to carry out, but it is not a pure optical realization and relies on some electronics devices (CCD, Computer and SLM), and it may not be implemented in real time. Therefore, we present both two approaches, and people can choose a better one according to practical applications.

#72115 - $15.00 USD Received 19 June 2006; revised 18 August 2006; accepted 21 August 2006

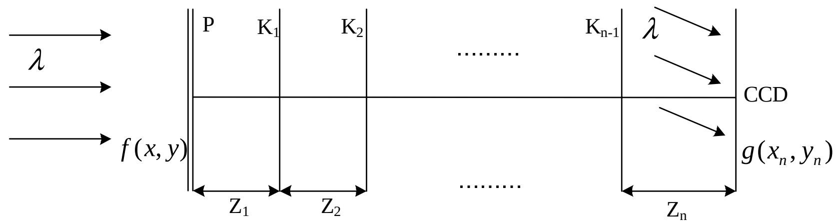

Fig. 4. Optoelectronic color image encryption architecture. SLM: Spatial Light Modulator; CCD: Charge-Coupled Device.

Figure 5 and Fig. 6 are the corresponding decryption realizations for the above two encryption systems. The conjugated encrypted data is placed at the input plane and passes through distances z_n, z_{n-1} z_2, z_1, with the phase masks K_{n-1} K_2, K_1 placed at corresponding positions in each channel. And finally the decryption image would be reconstructed at the output plane if all the keys were correct.

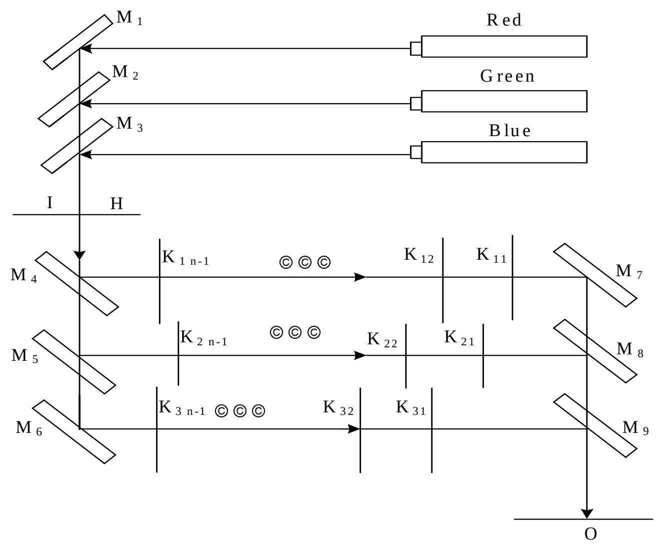

Fig. 5. Optical color image decoding realization. O: Output plane.

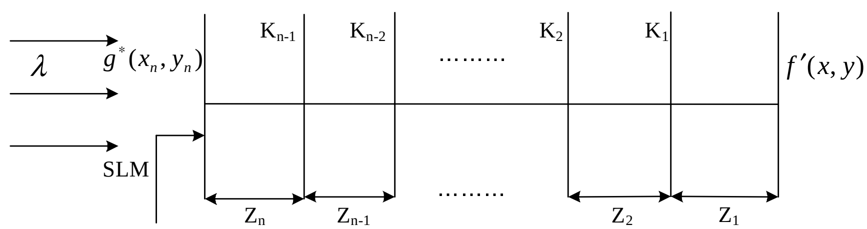

Fig. 6. Optoelectronic color image decryption configuration.

In above color image encryption systems, the information is encrypted independently in three channels and the iterative encryption method increases the keys rapidly, the keys in all these channels should be correct in decryption, otherwise the color information cannot be correctly recovered. In the following section, we give some computer simulation results based on the concept of digital hologram and virtual optics.

#72115 - $15.00 USD Received 19 June 2006; revised 18 August 2006; accepted 21 August 2006

4. Numerical simulations and analyses

Some numerical simulations have been performed in this section to verify the possibility of the proposed idea. The simulation results as shown in Fig. 7 and Fig. 8 are based on the setups in Fig. 3 to Fig. 6 and the method of digital hologram encryption technique. The fast Fourier transform (FFT) method and convolution algorithm is used for computing the Fresnel transform. A picture of a beautiful woman Lena is used as an original input image with 512×512 pixels as shown in Fig. 7(a). The actual size of the images and the phase masks are 10 mm in the simulations. Figure 7(b) is its encryption result. For the encryption of the first channel with red wavelength λ_1 =700nm, the system parameters are z_1=17mm, z_2=21mm, z_3=30.5mm, respectively. And the parameters of other two channels are λ_2 =546.1nm, z_1=20mm, z_2=25mm, z_3=28mm; λ_3 =435.8nm, z_1=16mm, z_2=23mm, z_3=47.7mm, respectively. $\lambda_1, \lambda_2, \lambda_3$ are the wavelengths of basic RGB color in the computer. The image is encrypted in three channels, and we can find the encrypted picture contains three noises (Red, Green and Blue). Here, z_1, z_2 and z_3 in each channel should be chosen carefully to reduce the size mismatch regarding the propagation distance.[4] Near-field diffraction is regarded as a better choice. Size mismatch also exists in each channel because different wavelength is used. A desired scale factor of the output can be obtained by adjusting the parameters of distances. Figure 7(c) shows one of the incorrect decryption images when random phase masks are incorrect in decryption. Then Fig. 7(d) gives the result with some wrong distance parameters (z_1=10mm, z_2=20mm, z_3=25mm; z_1=15mm, z_2=25mm, z_3=17mm; z_1=19mm, z_2=13mm, z_3=32mm). When random phase keys and system parameters are all wrong in decoding, the final decryption result is denoted in Fig. 7(e). Figure 7(f) is the correct decryption image.

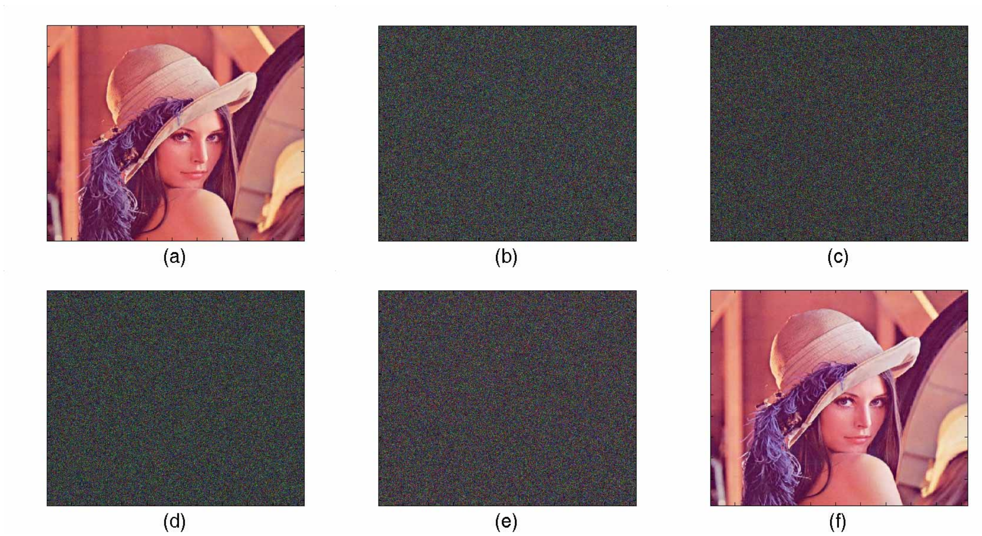

Fig. 7. Color image coding and decoding results. (a) Original image with 512×512 pixels; (b) encrypted result; (c)-(e) incorrect decryption image; (f) correct decryption image.

When only one or two channels are correctly decrypted, the correct color information also cannot be obtained. Figure 8(a) shows a flowers image with 500×362 pixels. Figure 8(b) is its encryption result. In Fig. 8(c) when the red component is incorrectly decrypted, the color of flowers such as lily and roses are changed to be green and this is a terrible thing because it transfers the pseudo information to people. While in Fig. 8(d), the green component is incorrectly decrypted, not only the color of flowers is distorted but also the leaves are impossible to be recognized. The same problem also exists in Fig. 8(e), when the blue color is incorrectly recovered, the background is changed from blue to green. But in Figs. 8(f)-8(h),

#72115 - $15.00 USD Received 19 June 2006; revised 18 August 2006; accepted 21 August 2006

the results are worse, for only one color component is correctly decoded, the reconstructed images are single color images with some noise of other color information. Finally, Fig. 8(i) gives the correct decryption result.

The normalized mean square error (MSE) between the reconstructed image and the original image is often used to verify the quality of the recovered image, which is described as

$$\mathrm{MSE}=\sum_{m=1}^{M}\sum_{n=1}^{N}\left[\left|f(m\Delta x,n\Delta y)-f_0(m\Delta x,n\Delta y)\right|^2\right]\Big/\sum_{m=1}^{M}\sum_{n=1}^{N}\left[\left|f(m\Delta x,n\Delta y)\right|^2\right], \tag{9}$$

where M and N are the pixels of the image, Δx and Δy are the pixel sizes. In this simulation, we give the MSEs of some decryption results. The MSE between the incorrect decryption image in Fig. 7(c) and original image in Fig. 7(a) is about 5.0860, and the corresponding MSE value between the correct decryption image in Fig. 7(f) and original image is about 5.1127×10^{-27}. The values of MSE are also calculated for the partial color information recovery situations as in Fig. 8. The MSE between Fig. 8(e) and Fig. 8(a) is about 1.8667, and the value is 3.5294 between Fig. 8(f) and the original image. We note that the values of MSE well reflect the quality of the decrypted images.

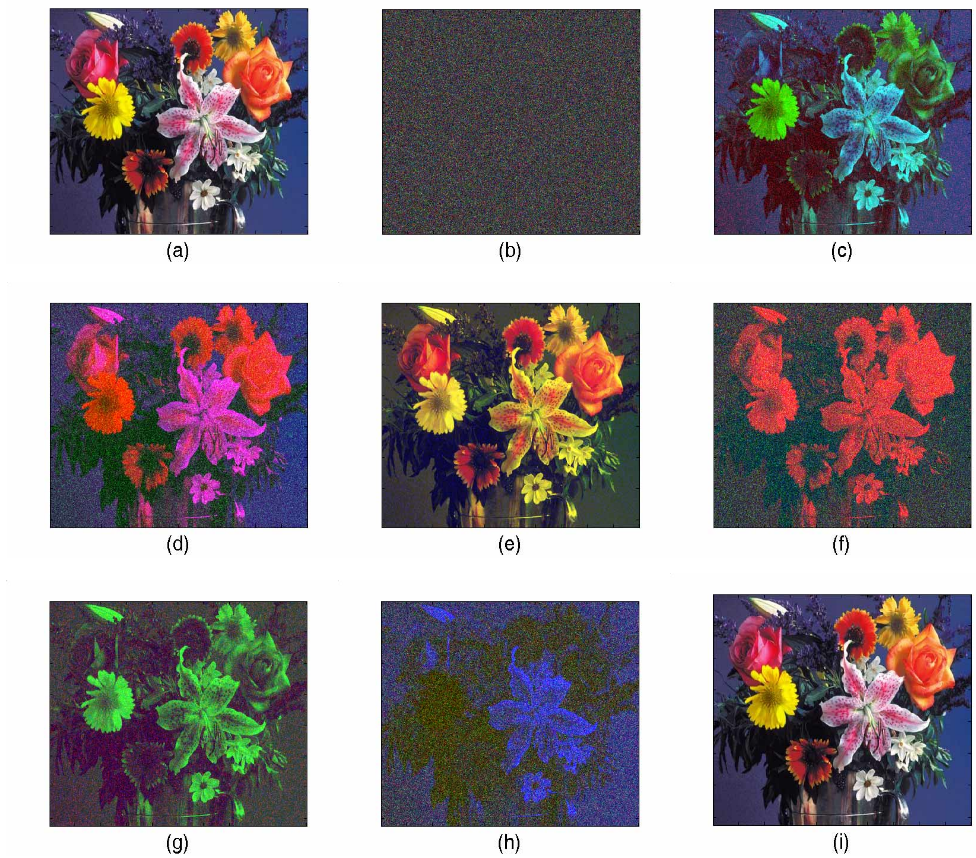

Fig. 8. Partial color image encryption and decryption results. (a) Original image with 500×362 pixels; (b) encryption image (c) result with red component incorrectly decrypted; (d) result with green component incorrectly decrypted; (e) result with blue component incorrectly decrypted; (f) only red component correctly decrypted; (g) only green component correctly decrypted; (h) only blue component correctly decrypted; (i) correct decryption.

5. Conclusion

In summary, we have proposed a useful method for color image encryption and it can be used both in optical and digital image encryptions. The random phase masks P and K_1, K_2, K_n, system parameters z_1, z_2, z_n in each channel are important keys in encryption and decryption. When the keys are incorrect in decryption, the noise like information would appear at the output plane. When keys of only one or two channels are correct, the color information is distorted, and people also cannot obtain the correct information. The keys can be enlarged further by employing more phase masks placed at Fresnel domains in each channel, and the synthesized information can be encrypted, stored and transmitted with high security.

Acknowledgment

This work was supported by the National Natural Science Foundation of China under grants 10276034 and 60478041.