Color digital holography using speckle illumination by means of a multi-mode fiber

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ABSTRACT

We present color digital holography using speckle illumination by means of a multi-mode fiber. In this technique, speckle fields emitted from the fiber are used as both a reference wave and a wavefront illuminating an object. For three wavelengths, the interference patterns of two coherent waves are recorded as digital holograms on a CCD camera. A speckle method is used for suppressing DC terms and reducing a twin image in an in-line color digital holography. The speckle fields are changed by vibrating the multi-mode fiber using a vibrator, and a number of holograms are acquired to average reconstructed images. The dependence of the averaged number of holograms on color quality of reconstructed images is evaluated by chromaticity coordinates and color differences in colorimetry.

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1. Introduction

It is known that digital holography is a technique for the recording and reconstruction of complex amplitudes of an optical field [1–4]. In this technique, an interference pattern of two coherent wavefronts is detected and digitized by an image sensor such as a CCD or CMOS camera, and digital holograms are saved into a computer. The wavefront is reconstructed from the digital holograms numerically. In a reconstruction process of the wavefront, DC terms, real and twin images are produced simultaneously. In an in-line setup, DC terms and a twin image are superimposed on a real image, which causes a degradation of image quality [5–8]. In off-axis [9–14] and phase-shifting digital holography [15–23], a real image is free from the degradation due to these cumbersome terms while these methods make a sacrifice of either temporal or spatial resolutions.

As an alternative method for reducing DC terms and a twin image in an in-line digital holography, a technique using a speckle illumination, which is called a speckle method, has been proposed [4,24,25]. In this technique, an object is illuminated with speckle fields generated from a diffuser. After acquiring a number of holograms using statistically independent speckle fields, DC terms are suppressed by applying a high-pass filter to each digital hologram [26]. Real and twin images reconstructed from multiple holograms are averaged for reducing the intensity fluctuation of real images due to speckle illuminations and eliminating a twin image. After the averaging process, intensity distributions of a twin image become a constant since it is regarded as a speckle field by the use of speckle illumination. Therefore, a twin image is eliminated by subtracting the constant from the reconstructed image. In comparison with the other methods, the speckle method has several advantages in that spatial resolution in the three-dimensional space and image quality are improved by the averaging process since speckle noises are reduced in reconstructed images and phase-shifting devices with high cost are not necessary. Meanwhile, it has disadvantages in that temporal resolution becomes lower due to the acquisition of a number of holograms and phase information of reconstructed images is not directly obtained since it is randomly modulated by the complex amplitude of speckle illuminations.

Recently, we proposed the speckle method by means of a multi-mode fiber in an in-line digital holography [27]. In this method, we use speckle fields emitted from a multi-mode fiber as both a reference wave and a wavefront illuminating an object. To capture multiple holograms in the speckle method, speckle fields are changed by vibrating the multi-mode fiber using a vibrator, which is composed of the DC motor with a speed controller. This method has several advantages in that (i) a simple optical system is realized by means of an optical fiber, (ii) it becomes easy to couple a coherent light into the optical fiber since multi-mode fibers have the larger core diameter in comparison with single-mode fibers and (iii) the speckle method can be readily performed by using speckle fields emitted from the fiber with a vibrator.

In the present paper, we report the application of this method to color digital holography, which is actively researched in 3D color imaging [28–38], recognition of a 3D color object [39], deformation...
measurement [40,41] and microscopy [42,43]. Although this technique can acquire the three-dimensional color information of an object, it has a disadvantage in that an optical system becomes quite complex due to the use of three lasers operating at different wavelengths. While an introduction of a fiber optic system is one of the methods for overcoming this disadvantage, it causes a reduction of optical powers in coupling laser lights with different wavelengths into an optical fiber, in particular, in the case of a single-mode fiber. This problem is mostly solved by means of a multi-mode fiber because of the larger core diameter. The proposed method has another advantage in that color quality of reconstructed images can be readily improved by averaging multiple holograms since color reconstructed images have low quality due to speckle noise. In addition, to the best of our knowledge, color digital holography using speckle illuminations has not been reported elsewhere.

In Section 2, we introduce the theoretical background of the recording digital holograms and reconstruction of wavefronts. Section 3 describes the suppression of DC terms and reduction of a twin image using the speckle method. In Section 4, we explain the color analysis of reconstructed images. The experimental results are shown in Section 5.

2. Recording digital holograms and reconstruction of wavefronts

Fig. 1 shows the schematic diagram of an optical geometry for recording digital holograms. It is based on an in-line digital holography. In this geometry, an image sensor is placed in the \((x_s, y_s)\) plane, which is called the hologram plane. A three-dimensional object and a light source are placed in the \((x_o, y_o)\) and \((x_s, y_s)\) plane, which is called the object and source planes. The object and source planes are located at distances \(d\) and \(d_s\) from the hologram plane.

A speckle field emitted from a multi-mode fiber is used as a reference wave, while an object wave is generated by illuminating the object with the speckle field. These waves interfere with each other and are detected on the image sensor. It digitizes holograms and digital holograms are acquired in a computer. Complex amplitudes of object and reference waves on the image sensor are derived from the Fresnel diffraction integral [44]. For simplicity, we carry out 1-D analysis, and constant terms and the integral regions which span from \(-\infty\) to \(\infty\) are omitted. The complex amplitude \(U_s(x_s)\) of the reference wave in the hologram plane is expressed as

\[
U_s(x_s) = \int u_{s1}(x_s) \exp \left[ \frac{j \pi}{\lambda d_s} (x_s - x_o)^2 \right] \, dx_s,
\]

where \(u_{s1}(x_s)\) is a speckle field emitted from a multi-mode fiber in the source plane, \(\lambda\) is the wavelength of an optical source and \(U_{s1}(x_s)\) is

\[
U_{s1}(x_s) = \int u_{s1}(x_s) \exp \left( \frac{j \pi}{\lambda d_s} x_s^2 \right) \, dx_s.
\]

In a similar fashion, we obtain the complex amplitude \(U_o(x_o)\) of an object wave in the hologram plane

\[
U_o(x_o) = \exp \left( \frac{j \pi}{\lambda d_o} \right) \mathcal{F}_{id}[u_{o2}(x_o) \exp \left( \frac{j \pi}{\lambda d_o} x_o^2 \right)]
\]

\[
= \exp \left( \frac{j \pi}{\lambda d_o} \right) \mathcal{F}_{id}[U_{o2}(x_o)],
\]

where \(u_{o2}(x_o)\) is the complex amplitude of a speckle field generated by the multi-mode fiber in the object plane, \(u_{o2}(x_o)\) is the complex amplitude of an object, \(\mathcal{F}_{id}[\cdot]\) stands for the Fourier transform modified by a factor of \(1/\lambda d_o\) and \(U_{o2}(x_o)\) is

\[
U_{o2}(x_o) = u_{o2}(x_o) \exp \left( \frac{j \pi}{\lambda d_o} x_o^2 \right) \cdot
\]

The intensity distribution \(I_{ii}(x)\) of the interference pattern of object and reference waves can be written as

\[
I_{ii}(x) = \left| U_o(x_o) + U_s(x_s) \right|^2 = \left| U_s(x_s) \right|^2 + \left| U_o(x_o) \right|^2 + U_s^*(x_s) U_o^*(x_o),
\]

\[
= \left| U_{s1}(x_s) \right|^2 + \left| U_{o2}(x_o) \right|^2 + U_{s1}^*(x_s) U_{o2}^*(x_o),
\]

where \(\ast\) stands for the complex conjugate and \(U_{s1}(x_s) = U_{s1}(x_s) U_{o2}^*(x_o)\). In Eq. (5), the third term is a real image

\[
U_{rec}(x) = \mathcal{F}_{id}^{-1}[S_{f}(x)|I_{ii}(x)|]
\]

\[
= \int I_{ii}(x) \exp \left( - \frac{j \pi}{\lambda d_s} x_s^2 \right) \exp \left( \frac{2j \pi}{\lambda d_o} x_o \right) \, dx_s
\]

\[
= \mathcal{D}_{d_s} \left[ \left| U_{s1}(x_s) \right|^2 + \left| U_{o2}(x_o) \right|^2 + U_{s1}^*(x_s) U_{o2}^*(x_o) \right],
\]

where \(S_{f}(x)\) is the coordinate in the reconstruction plane, \(\mathcal{D}_{d_s}[\cdot]\) stands for the optical propagation from the hologram plane to the reconstruction plane and \(S_{f}(x)\) is the quadratic phase factor for focusing a real image expressed as

\[
S_{f}(x) = \exp \left( \frac{j \pi}{\lambda d_{f}} x_s^2 \right).
\]

In Eq. (9), the first, second and third terms are DC terms, real and twin images, respectively.

In digital holography, an intensity distribution in Eq. (5) is sampled by an image sensor and saved into a computer. A numerical reconstruction of the object wave is performed by the fast Fourier transform of digital holograms. The discrete form of Eq. (8) is expressed for integers \(p\) and \(q\) as

\[
u_{rec}(q\Delta') = \frac{N/2 - 1}{p} \sum_{p = -N/2}^{N/2 - 1} I_{ii}(p\Delta) \exp \left( \frac{j \pi}{\lambda d_o} q\Delta p \right)
\]

\[
\times \exp \left( \frac{2j \pi}{\lambda p} q\Delta p \right)
\]

for \(q = -N/2, -N/2 + 1, \ldots, N/2 - 1\), where \(N\) is the data size of digital holograms, and \(\Delta\) and \(\Delta'\) are the pixel sizes of an image sensor and the reconstruction plane, respectively. The coordinates \(x_s\) and \(x_o\) are converted into \(p\Delta\) and \(q\Delta'\). The pixel size \(\Delta'\) and the field...
of view V in the reconstruction plane are expressed as
\[ \Delta' = \frac{\lambda d}{N A}, \quad V = \frac{\lambda d}{\Delta} \] (12)

Although the theoretical background in the discrete coordinate should be explained in digital holography, we will use a continuous coordinate for simplicity and brevity.

3. Speckle method

In an in-line digital holography, it is desirable to remove or suppress DC terms and a twin image since these images overlap with a real image and therefore image quality becomes lower [5–8]. In the present paper, the speckle method is used for reducing these terms [24,25]. In this method, a number of digital holograms are captured by the CCD camera, and the reconstructed images are averaged in intensity basis since the real image reconstructed from a single hologram becomes low quality due to the spatial variation of a speckle intensity incident on the object.

3.1. Suppression of DC terms

For suppressing DC terms in holograms, several high-pass filters are proposed. The properties of these filters are derived theoretically [26,45] and demonstrated experimentally [24]. As a preprocessing before averaging reconstructed images of multiple holograms, DC terms are suppressed by the numerical technique based on high-pass filtering of digital holograms in the spatial frequency region [24,26]. The Fourier spectrum of digital holograms is filtered by a Gaussian filter expressed as
\[ g(f_s) = \exp \left( -\frac{f_s^2}{w^2} \right), \] (13)

where \( f_s \) is the spatial frequency coordinate of a hologram and \( w \) is the extent of the Gaussian filter. A smoothed hologram is produced by applying the inverse Fourier transform to the filtered spectrum. DC terms could be suppressed by subtracting the smoothed hologram from the original one, which is a role in a high-pass filtering of the original hologram.

3.2. Averaging process of reconstructed images

After suppressing DC terms, reconstructed images are averaged. Now, we notice the term of a real image in Eq. (9). It is expressed as
\[ \mathcal{D}_h[U_s(x_0)] = \mathcal{F}^{-1}_d[U_1(x_0)F_d[U_2(x_0)]] \]
= \( \mathcal{F}^{-1}_d[U_1(x_0)] \otimes u_{s2}(x_0), \) (14)

where \( \otimes \) stands for the convolution operation. The averaged intensity distribution of the real image is obtained by subtracting the smoothed hologram from the original one, which is a role in a high-pass filtering of the original hologram.

3.3. Reduction of twin image

Next, we consider the reduction of a twin image. After suppressing DC terms and averaging reconstructed images, intensity distributions in Eq. (9) are rewritten as
\[ I_{rec}(\lambda) = |\langle \mathcal{D}_h[U_s(x_0)] \rangle|^2 + |\langle \mathcal{D}_h[U_s^*(x_0)] \rangle|^2. \] (20)

It is assumed that the intensity distributions of a twin image uniformly spread over the reconstruction plane and can be regarded as speckle fields. Since real and twin images have the same energies, the averaged intensity of a twin image is approximately derived from
\[ |\langle \mathcal{D}_h[U_s^*(x_0)] \rangle|^2 = \frac{E_1}{2N^2}, \] (21)

where \( E_1 \) is the total intensity of the reconstructed image. The twin image is reduced by subtracting the value in Eq. (21) from the intensities of reconstructed images.

4. Color analysis

To evaluate color quality of the reconstructed image in color digital holography, we use chromaticity coordinates and color differences in colorimetry [46]. The tristimulus values X, Y, and Z are expressed in the CIE 1931 supplemental colorimetric standard system as
\[ X = k \int_{700}^{400} S(\lambda)O(\lambda)\xi(\lambda) \, d\lambda \]
\[ Y = k \int_{700}^{400} S(\lambda)O(\lambda)\nu(\lambda) \, d\lambda \]
\[ Z = k \int_{700}^{400} S(\lambda)O(\lambda)\zeta(\lambda) \, d\lambda, \] (22)

where \( S(\lambda) \) and \( O(\lambda) \) are the spectra of a light source and an object, \( \xi(\lambda), \nu(\lambda) \) and \( \zeta(\lambda) \) are the two-degree color-matching functions and
\[ k = \frac{100}{\int_{400}^{700} S(\lambda)O(\lambda) \, d\lambda}. \] (23)

A color image is obtained by the transformation of the tristimulus values to the sRGB color space, which is given by
\[ \begin{bmatrix} R \\ G \\ B \end{bmatrix} = M \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \] (24)

where \( M \) is the transformation matrix, and \( R, G, \) and \( B \) are the values of red, green, and blue in each pixel of a color image. In addition, the chromaticity coordinates are given by
\[ x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad z = \frac{Z}{X+Y+Z}. \] (25)
Color differences are also derived from the tristimulus values, which are used for calculating the CIELAB color space. It is given by

\[
L^* = \begin{cases} 
116 \left( \frac{Y}{Y_n} \right)^{1/3} - 16 & (Y/Y_n > 0.008856) \\
903.3 \left( \frac{Y}{Y_n} \right) & (Y/Y_n \leq 0.008856)
\end{cases}
\]

\[
\Delta L^* = X_n \left( \frac{X}{X_n} \right)^{1/3} - \left( \frac{X}{X_n} \right)^{1/3}
\]

\[
\Delta a^* = 500 \left( \frac{Y}{Y_n} \right)^{1/3} - \left( \frac{Y}{Y_n} \right)^{1/3}
\]

\[
\Delta b^* = 500 \left( \frac{Z}{Z_n} \right)^{1/3} - \left( \frac{Z}{Z_n} \right)^{1/3},
\]

where \(X_n, Y_n\) and \(Z_n\) are the values of the tristimulus values for the appropriately chosen reference white, which is a perfect reflecting diffuser in the present paper. If the differences between two colors in \(L^*, a^*,\) and \(b^*\) are denoted by \(\Delta L^*, \Delta a^*,\) and \(\Delta b^*,\) then the color difference \(\Delta E\) is evaluated from

\[
\Delta E = (\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)^{1/2}.
\]

5. Experiment

Fig. 2 shows the experimental setup for recording color digital holograms. Optical sources are DPSS lasers and a He–Ne laser with the wavelengths of 473 nm (Spectra physics, EXLSR–473TL–KE, 10 mW), 532 nm (Thorlabs, DJ532–40, 40 mW) and 632 nm (NEC Corporation, GLG5410, 20 mW), respectively. The coherent lights emitted from the three lasers are launched into a multi-mode fiber by an objective lens OB. It is a \(1 \times 2\) step-index multi-mode fiber with a core diameter of 400 \(\mu\)m (Ocean Optics, SPT400-UV-VIS, NA= 0.22 ± 0.02, 2 m), which is selected to readily change the spatial distributions of speckle intensities emitted from the fiber and improve the coupling efficiency of the fiber for three wavelengths.

Speckle patterns with three wavelengths are guided and split by the fiber. One of the split lights is incident on a test object, where object waves are produced. The other is reflected by a beam splitter (BS) and used as speckled-reference waves. The object and reference waves are coupled by the beam splitter (BS) again, interfere each other and are detected on a monochrome CCD camera (AVT, GC2450) having 2448 \(\times\) 2050 pixels with a pixel pitch of \(\Delta x = 3.45 \mu m\). For the three wavelengths, holograms are acquired by the camera separately. All holograms are recorded with \(N \times n = 2048 \times 2048\) pixels initially.

A test object is a part of a doll with 10.0 mm \(\times\) 12.8 mm, which is shown in Fig. 3. Speckle patterns are temporally and randomly changed by vibrating the multi-mode fiber using a vibrator, which is composed of a DC motor with a speed controller [47,48]. For each wavelength, the multiple holograms are sequentially recorded by the CCD camera at 10.57 fps. The revolution of the motor is set to 500 rpm. Thirty holograms are recorded as a movie to average reconstructed images in this experiment. To improve image quality in the speckle method, statistically uncorrelated or independent holograms are desirable. To evaluate it, cross-correlation coefficients of each hologram are calculated by

\[
C(i,j) = \frac{1}{n^2 \sigma_f^2} \left\{ \frac{1}{n} \sum_{i=1}^{n} \sum_{j=1}^{n} [I_i(x_h) - \langle I_i \rangle] [I_j(x_h) - \langle I_j \rangle] \right\},
\]

where \(i \neq j, I_i(x_h)\) is an intensity distribution of holograms, \(\langle I_i \rangle\) and \(\sigma_f\) are the mean and standard deviation of \(I_i(x_h), n\) is the number of holograms which are used in the averaging process. Fig. 4(a)–(c) show histograms of cross-correlation coefficients in thirty holograms for three wavelengths. The means and standard deviations of the cross-correlation coefficients of the thirty holograms are 0.08 and 0.11 for 473 nm, 0.09 and 0.16 for 532 nm and 0.19 and 0.20 for 632 nm, respectively.

For the estimation of the reconstruction distance of real images, the contrast of the reconstructed images is used [49], in which the sharpness of images is evaluated by an image contrast for each propagation distance. The holograms are reconstructed by the

![Fig. 2. Experimental setup for color digital holography.](image)

![Fig. 3. Test object.](image)
Fig. 4. Histograms of cross-correlation coefficients in thirty holograms for (a) 473 nm, (b) 532 nm and (c) 632 nm, respectively.

Fig. 5. Experimental results of the reconstructed images after suppressing DC terms and reducing a twin image. (a), (c) and (e) are the reconstructed images from one hologram, and (b), (d) and (f) are the reconstructed images after averaging thirty holograms. The wavelengths in recording holograms are 473 nm for (a) and (b), 532 nm for (c) and (d) and 632 nm for (e) and (f).
single-FFT method. The reconstruction distances of real images are obtained by the peak values of it and calculated to be \(d_f = 160\) mm for three wavelengths.

Next, the suppression of DC terms is performed by means of the Gaussian high-pass filter in Eq. (13). The widths \(w_f = 49, 57\) and 65 pixels are used for 473, 532 and 632 nm, respectively. After suppressing DC terms, the reconstructed images are averaged by multiple holograms. Fig. 5(a)–(f) shows experimental results of reconstructed images after suppressing DC terms and reducing a twin image for three wavelengths. Fig. 5(a), (c) and (e) is the reconstructed image from one hologram, and Fig. 5(b), (d) and (f) is the reconstructed image after averaging thirty holograms. Wavelengths in recording holograms are 473 nm for (a) and (b), 532 nm for (c) and (d) and 632 nm for (e) and (f). It is found in these figures that image quality of real images is improved in Fig. 5(b), (d) and (f) in comparison with Fig. 5(a), (c) and (e). Fig. 6 shows the speckle contrasts of the reconstructed images with three wavelengths for the number of holograms. This figure shows that the speckle contrasts decrease with an increase in the number of holograms for each wavelength, which implies that the intensity fluctuation due to the speckle illumination is reduced by averaging reconstructed images and image quality is improved. The speckle contrasts in Fig. 6 gradually converges and image quality of the real image does not change any more after averaging fifteen holograms in the present case [50].

It is seen in Eq. (12) that the mismatch of a spatial position occurs in each pixel of reconstructed images since the pixel sizes depend on wavelength in the reconstruction process of the single-FFT method, which causes the degradation in the color reproduction process. For adjusting the pixel sizes of reconstructed images in three wavelengths, we use the zero-padding method [51].

Fig. 7(a)–(c) shows the reconstructed images in the sRGB color space after the color reproduction process. It is seen from these figures that image quality of the color image is improved as is the case with Fig. 5. The color distributions in the marginal region of the real image are residual twin images, which remain because the assumption in Eq. (21) is not strictly satisfied in this case. To quantitatively evaluate image quality in colorimetry, chromaticity coordinates and color differences are calculated by using Eqs. (25) and (27). Fig. 8(a)–(c) shows the two-dimensional frequency distributions in the chromaticity coordinates of Fig. 7(a)–(c). The

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**Fig. 6.** Speckle contrasts of reconstructed images for the averaged number of holograms in each color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Fig. 7.** Experimental results of the color images. (a) One hologram; (b) ten holograms; (c) thirty holograms.

**Fig. 8.** Two-dimensional frequency distributions in the chromaticity coordinates of Fig. 7(a)–(c). The color bar means the frequency on a logarithmic scale. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
horseshoe-shaped curve in the white solid line and its inside are spectral colors and the full color space. The triangle areas are a true color space composed of the spectral colors in the three wavelengths. It is seen in these figures that the frequency distributions center around the white color \((x, y)=(1/3, 1/3)\) with an increase in the holograms used in the averaging process and are biased toward a pale color, which corresponds with the color distribution in the test object shown in Fig. 3.

Fig. 9 shows the mean and standard deviation of color differences for the averaged number of holograms. To calculate the color difference, the color image after averaging thirty holograms is used as the reference of the color distribution. It is found in these figures that the mean and standard deviation of color differences slowly converge in comparison with speckle contrasts shown in Fig. 6 and is high even in the case of twenty holograms since \(\Delta F \geq 3.0\) is regarded as the different color in human eyes.

6. Conclusion

In the present paper, we reported color digital holography using speckle illumination by means of a multi-mode fiber. In this technique, speckle fields with three wavelengths were emitted from the fiber and were used as both a reference wave and a wavefront illuminating an object. The interference patterns of two coherent waves were recorded as digital holograms on a CCD camera for the three wavelengths. The speckle fields were changed by vibrating the multi-mode fiber using a vibrator, and a number of holograms were acquired to average the reconstructed images. The speckle method was used for suppressing DC terms and reducing a twin image in an in-line color digital holography. The color quality of reconstructed images was evaluated for the averaged number of holograms by chromaticity coordinates and color differences in colorimetry. In conclusion, the proposed method has several advantages in that a simple optical system is realized by means of an optical fiber, the coupling efficiency of an optical fiber in three wavelengths is improved by means of a multi-mode fiber and image quality of color reconstructed images can be improved by the speckle method.

References

[1] J.W. Goodman, R.W. Lawrence, Applied Physics Letters 11 (1967) 77.
[2] U. Schnars, Journal of the Optical Society of America A 11 (1994) 2011.
[3] U. Schnars, W. Jueptner, Digital Holography, Springer, New York, 2005.
[4] M.K. Kim, Digital Holographic Microscopy, Springer, New York, 2011.
[5] H.J. Tiziani, G. Pedrini, Y.L. Zou, Journal of Modern Optics 42 (1995) 367.
[6] Y. Zhang, G. Pedrini, W. Osten, H.J. Tiziani, Optics Letters 29 (2004) 1787.
[7] G. Situ, J.P. Ryle, U. Gopinathan, J.T. Sheridan, Applied Optics 47 (2008) 711.
[8] B. Das, C.S. Veelawarapu, Optics Letters 35 (2010) 3426.
[9] U. Schnars, W. Jueptner, Applied Optics 33 (1994) 179.
[10] E. Cuche, P. Marquet, C. Depeursinge, Applied Optics 39 (2000) 4070.
[11] N. Pavillon, C. Affire, I. Bergoend, C. Depeursinge, Optics Express 18 (2010) 15318.
[12] H. Funamizu, Y. Aizu, Applied Optics 50 (2011) 6011.
[13] H. Funamizu, T. Kato, Y. Aizu, Y. Ishii, Optics Communications 285 (2012) 4987.
[14] H. Funamizu, J. Uozumi, Y. Aizu, Journal of Optics 15 (2013) 035704.
[15] I. Yamaguchi, T. Zhang, Optics Letters 22 (1997) 1268.
[16] T. Zhang, I. Yamaguchi, Optics Letters 23 (1998) 1221.
[17] C.-S. Guo, L. Zhang, H.-T. Wang, J. Liao, Y.Y. Zhu, Optics Letters 27 (2002) 1687.
[18] T. Nomura, B. Javidi, S. Murata, E. Nitanai, T. Numata, Optics Letters 32 (2007) 481.
[19] S. Tamano, M. Okha, Y. Hayasaka, Japanese Journal of Applied Physics 47 (2008) 8844.
[20] J.-P. Liu, T.-C. Poon, Optics Letters 34 (2009) 250.
[21] T. Nomura, M. Imre, Optics Letters 35 (2010) 2281.
[22] Y. Awatsuji, M. Sasada, T. Kubota, Applied Physics Letters 85 (2004) 1069.
[23] T. Tahara, Y. Shimozato, Y. Awatsuji, K. Nishio, S. Ura, O. Matoba, T. Kubota, Optics Letters 37 (2012) 148.
[24] D.S. Monaghan, D.P. Kelly, N. Pandey, B.M. Henelly, Optics Letters 34 (2009) 3610.
[25] Y.K. Park, W. Choi, Z. Yapoooh, R. Dasari, K. Badizadegan, M.S. Feld, Optics Express 17 (2009) 12285.
[26] T.M. Kreis, W.P.O. Juptner, Optical Engineering 36 (1997) 2357.
[27] H. Funamizu, S. Shimoza, Y. Aizu, Optics Communications 305 (2013) 100.
[28] I. Yamaguchi, T. Matsumura, J. Kato, Optics Letters 27 (2002) 1108.
[29] J. Kato, I. Yamaguchi, T. Matsumura, Optics Letters 27 (2002) 1403.
[30] B. Javidi, P. Ferraro, S.H. Hong, S. De Nicola, A. Finizio, D. Alfieri, G. Pierattini, Optics Letters 30 (2005) 144.
[31] D. Alfieri, G. Coppola, S. De Nicola, P. Ferraro, A. Finizio, G. Pierattini, B. Javidi, Optics Communications 260 (2006) 113.
[32] J. Zhao, H. Jiang, J. Di, Optics Express 16 (2008) 2514.
[33] T. Kakue, T. Tahara, K. Ito, Y. Shimozato, Y. Awatsuji, K. Nishio, S. Ura, T. Kubota, G. Matoba, Applied Optics 48 (2009) H244.
[34] T. Kakue, M. Kuvamura, Y. Shimozato, T. Tahara, Y. Awatsuji, K. Nishio, S. Ura, T. Kubota, O. Matoba, Optical Review 18 (2011) 180.
[35] H. Jiang, J. Zhao, J. Di, Optics Communications 285 (2012) 3046.
[36] T. Kiiie, K. Barada, J. Sugisaka, Y. Hayasaka, T. Yataga, Optics Letters 37 (2012) 3153.
[37] P. Memmolo, A. Finizio, M. Paturzo, P. Ferraro, B. Javidi, Optics Letters 37 (2012) 1445.
[38] H.K. Kim, Optics Express 21 (2013) 9636.
[39] S. Yeom, B. Javidi, P. Ferraro, D. Alfieri, S. De Nicola, A. Finizio, Optics Express 15 (2007) 9394.
[40] N. Demoli, D. Vukicevic, M. Torzynski, Optics Express 11 (2003) 767.
[41] P. Picart, D. Moumer, J.M. Desse, Optics Letters 33 (2008) 276.
[42] P. Ferraro, S. Grilli, L. Miccio, D. Alfieri, S. De Nicola, A. Finizio, B. Javidi, Journal of Display Technology 4 (2008) 97.
[43] J.C. Sureauca, Optics Letters 37 (2012) 1724.
[44] J.W. Goodman, Introduction to Fourier Optics, Roberts & Company, CO, 2005.
[45] K.M. Pavlov, D.M. Paganin, D.J. Vine, J.A. Schmalz, Y. Suzuki, K. Uesugi, A. Takeuchi, N. Yagi, A. Kharchenko, G. Blaj, J. Jakubek, M. Altissimo, J.N. Clark, Physical Review A 83 (2011) 013813.
[46] R.W.G. Hunt, Measuring Color, Fountain Press, England, 1998.
[47] N. Takai, T. Asakura, Journal of the Optical Society of America A 2 (1985) 1282.
[48] N. Takai, T. Asakura, Journal of the Optical Society of America A 3 (1986) 1305.
[49] P. Memmolo, C. Distante, M. Paturzo, A. Finizio, P. Ferraro, B. Javidi, Optics Letters 36 (2011) 1945.
[50] J.W. Goodman, Speckle Phenomena in Optics: Theory, Applications, Roberts & Co, CO, 2006.
[51] P. Ferraro, S. De Nicola, G. Coppola, A. Finizio, D. Alfieri, G. Pierattini, Optics Letters 29 (2004) 854.