Pattern composed of two-dimensional diffusion dots for showing dynamic images

Sheng Lih Yeh,1,* Kuang Tsan Lin,2 and Yu Jui Cheng3

1Department of Mechanical Engineering, Lunghwa University of Science and Technology, 300, Section 1, Wanshou Road, Kueishan Taoyuan County, Taiwan
2Department of Mechanical and Computer Aided Engineering, Saint John’s University, 499, Section 4, Tam King Road, Tamsui, Taipei County, Taiwan
3Institute of Engineering Technology, Lunghwa University of Science and Technology

*Corresponding author: slyeh@mail.lhu.edu.tw

Received 14 November 2006; revised 22 January 2007; accepted 2 February 2007; posted 5 February 2007 (Doc. ID 77003); published 18 May 2007

A new type of diffusion pattern is proposed. The proposed patterns are composed of 2D diffusion dots. The diffusion dots are created on a photoresist plate by recording the image of a local area of a piece of ground glass dot by dot. An imaging lens covered by a mask with a slit aperture is used to form the image. By changing the orientation of the slit aperture on the mask plane, the diffusion dots can have different microintensity distributions for the same incident light beam. Therefore the diffusion dots created by the same slit aperture orientation show the same brightness, and the diffusion dots created by different slit orientations show different brightness for the same illuminating and viewing conditions. Thus a proposed diffusion pattern can show dynamic images by changing its illuminating or viewing directions. By applying the double-exposure technique to the diffusion dots of a pattern, the pattern not only can show dynamic effects but also can possess several hidden features for identifying the pattern. Therefore the proposed patterns are dynamic and anticounterfeiting. © 2007 Optical Society of America

OCIS codes: 110.6150, 290.1990.

1. Introduction
For enhancing the anticounterfeiting capacity of commercial products, attaching holograms on the products is very popular. Many hologram patterns are created by 2D grating dots (grating-dot patterns), so they can display dynamic images and can have anticounterfeiting capacity [1–4]. However, some users like hologram patterns with diffusion images (diffusion patterns) [5,6] for the following reasons: (1) For a white-light source, the image color displayed by a diffusion pattern is always white (independent of the illuminating condition of the light source), but the image color displayed by a grating-dot pattern is variable (dependent on the illuminating and viewing conditions). Therefore diffusion patterns are preferred for cases to show trademarks. (2) For some products the appearances of patterns attached on them must be similar to those of their surfaces. The appearance of a diffusion pattern is similar to that of an iron or aluminum surface with great roughness, but the appearance of a grating-dot pattern is not. Therefore diffusion patterns are preferred for the above products. (3) The image shown by a diffusion pattern can be seen from a larger viewing direction range, but the image shown by a grating-dot pattern can be seen only from a smaller viewing direction range. Therefore diffusion patterns are preferred for cases in which larger viewing direction ranges are needed.

Of course, the features to show dynamic images and to have anticounterfeiting capacity must be retained when diffusion patterns are used to replace grating-dot patterns. Therefore diffusion patterns will be created by 2D exposure and useful anticounterfeiting methods for diffusion patterns will be analyzed in this paper.

2. Theory
Figure 1 shows a setup to create a pattern with 2D diffusion dots. A laser beam is normally incident on
a piece of ground glass, and the beam is scattered by the ground glass. A mask M1 is set just before or just behind the ground glass to constrain the scattering area on the ground glass. An imaging lens is used to collect the scattered light to image the constrained area of the ground glass on a photoresist plate. Because the image is created by the interference of many spherical waves diverged from the ground glass surface, the recorded image on the photoresist plate contains many elementary gratings with different grating pitches and different grating orientations [5]. Therefore the recorded image can scatter (by multigrating diffraction) a light beam incident on it. The recorded image performs like a diffuser and is small, so it is called a diffusion dot. The imaging lens is covered by a mask M2 with a long slit aperture, then the scattering features of the recorded image depend on the parameters of the slit aperture. The photoresist plate is put on two translation stages to control its 2D position on the plate plane. Therefore 2D diffusion dots can be recorded on the plate dot by dot.

In Fig. 1, the ground glass surface, the imaging lens, and the diffusion dot are on the $x_1$-$y_1$, $x_2$-$y_2$, $x_3$-$y_3$ planes, respectively. $U_1$ (modulated by the ground glass and the mask M1) and $U_2$ denote the amplitude fields on the $x_1$-$y_1$ and $x_3$-$y_3$ planes, respectively. The slit aperture on the mask M2 has a function $P(x_2, y_2)$. $d_o$ is the object distance, $d_i$ is the image distance, and $M = d_i/d_o$ is the photo-reduction ratio. Therefore (neglecting the unimportant constants) [5]

$$U_3(x_3, y_3) = h(x_3, y_3) \otimes U_2(x_3, y_3),$$  \hspace{1cm} (1a)

$$h(x_3, y_3) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(x_2, y_2) \times \exp[-j2\pi(x_3\hat{x} + y_3\hat{y})]dx\,dy, \hspace{1cm} (1b)$$

$$U_2(x_3, y_3) = \frac{1}{M} U_1\left(-\frac{x_3}{M}, -\frac{y_3}{M}\right), \hspace{1cm} (1c)$$

where $\otimes$ denotes a convolution operation, $j = \sqrt{-1}$, $\hat{x} = x_2/\lambda_d$, $\hat{y} = y_2/\lambda_d$, and $\lambda_1$ is the wavelength of the laser for exposure. The intensity distribution $I_3(x_3, y_3)$ on the $x_3$-$y_3$ plane is

$$I_3(x_3, y_3) = |U_3(x_3, y_3)|^2. \hspace{1cm} (2)$$

Suppose that the relationship of the intensity distribution $I_3(x_3, y_3)$ and the transmission function $t(x_3, y_3)$ of the exposed diffusion dot is

$$t(x_3, y_3) = \exp[j(c_1 + c_2 I_3(x_3, y_3))], \hspace{1cm} (3)$$

where $c_1$ and $c_2$ are constants.

The scattering behavior (by diffraction) of the diffusion dot illuminated by a laser beam is shown in Fig. 2. A parallel-wave light $R(x_i, y_i) = \exp[2\pi(x_i \sin \alpha + y_i \cos \alpha)/\lambda_2]$ is used to illuminate the diffusion dot on the $x_i$-$y_i$ plane, where $\lambda_2$ is the light wavelength of the laser beam, $\alpha$ is the angle between the light progress
direction and the $y_z$ plane, and $\beta$ is the angle between the light progress direction and the $x_z$ plane. The diffusion light field is projected on the $x_z$ plane. The distance between the $x_i$ and $x_z$ planes is $s$. When $s$ is much larger than the size of the diffraction dot, the diffraction light field on the $x_z$ plane is similar to the Fourier transformation of the light field $U_i(x_i, y_i) = t(x_i, y_i)R(x_i, y_i)$ just behind the diffraction dot. For convenience, let $u = x_i/\lambda_2 s, v = y_i/\lambda_2 s, \xi = \sin \alpha/\lambda_2$, and $\eta = \sin \beta/\lambda_2$. The Fourier spectrum $\tilde{U}_i(u, v; \xi, \eta)$ of the amplitude field $U_i(x_i, y_i)$ is

\[
\tilde{U}_i(u, v; \xi, \eta) = c_3 F\{\exp[jc_3 I_3(x_3, y_3)]\}_{u=x_i, v=y_i, \xi \rightarrow \infty, \eta \rightarrow \infty} = \tilde{U}_i(u - \xi, v - \eta; 0, 0),
\]

where, $c_3 = \exp(jc_1)$. Equation (4) shows that (1) the diffraction light field $\tilde{U}_i(u, v; \xi, \eta)$ is shift invariant with $u - \xi$ and $v - \eta$, i.e., the spectrum shifts when the laser beam changes its incident direction; (2) the scale of $\tilde{U}_i(u, v; \xi, \eta)$ is proportional to $\lambda_2$, i.e., there is dispersion for the diffraction.

(1) For the case in which $c_3 I_3(x_3, y_3)$ is small (corresponding to a case with less exposure energy), $\tilde{U}_i(u, v; \xi, \eta)$ approaches

\[
\tilde{U}_i(u, v; \xi, \eta) = c_4 \delta(u - \xi, v - \eta) + c_4 \left[\tilde{H}(u - \xi, v - \eta) \times \tilde{U}_i(u - \xi, v - \eta)\right] \oplus \left[\tilde{H}(u - \xi, v - \eta) \times \tilde{U}_i(u - \xi, v - \eta)\right],
\]

where, $c_4 = j(c_2)^2, \oplus$ denotes a correlation operation, and $\tilde{H}(u, v)$ and $\tilde{U}_i(u, v)$ are the Fourier transformations of $h(x_3, y_3)$ and $U_i(x_3, y_3)$, respectively. Equation (5) discloses that the light field diffracted by the diffusion dot contains a nondiffracted spot and a diffracted bright area (corresponding to a scattering direction range for the diffusion dot to look bright).

(2) For the case in which $c_3 I_3(x_3, y_3)$ is not small (corresponding to a case with more exposure energy), $\tilde{U}_i(u, v; \xi, \eta)$ cannot be simplified, and Eq. (4) must be operated with experiments. According to the experimental results in the next section, a case with more exposure energy has similar diffraction features (a nondiffracted spot and a diffracted bright area) as one with less exposure energy.

Therefore a diffracted bright area always appears on the Fourier spectrum when a diffusion dot is illuminated by a laser beam. The function $U_i(x_i, y_i)$ usually is a symmetric function, so the function $\tilde{U}_i(u, v)$ is too. According to Eq. (5), the diffracted bright area is dominated by the autocorrelation value $\tilde{H}(u, v) \oplus \tilde{H}(u, v) = P(-x_2, -y_2) \oplus P(-x_2, -y_2)$, and different $P(x_2, y_2)$ functions can be used to make 2D diffusion dots have different scattering direction ranges. The simplest method to change the function $P(x_2, y_2)$ for different diffusion dots is by rotating the slit aperture about the optical axis of the imaging lens. On the other hand, the simplest aperture useful to control the scattering direction range of a diffusion dot is a long rectangle. As a result, the diffusion dots created by the same slit aperture orientation show the same brightness (gray level), and the diffusion dots created by different slit aperture orientations show different brightness. Therefore the pattern composed of many diffusion dots with different slit aperture orientations can show different appearance when the light source changes its position, the pattern plane is rotated, or the eyes of a viewer change their positions. Because the autocorrelation of the slit aperture function $P(x_2, y_2)$ dominates the response of the pattern for an incident beam, the slit aperture orientations $\theta$ and $\theta + 180^\circ$ induce the same diffraction feature. Therefore the range $-90^\circ \leq \theta < 90^\circ$ is enough for all grating dots.

Because a diffusion dot contains many different elementary gratings, the serious diffractive dispersion of the gratings is suppressed by the multicolor overlapping of the many elementary gratings. Therefore a diffusion dot always looks black and white.

Every diffusion dot can be exposed one or two times. When a dot is exposed one time only, it is single exposed. When a dot is exposed twice, it is double exposed, and the positions of the two exposed

---

Fig. 2. Light scattered by a diffusion dot created by the setup in Fig. 1.
areas can be different (note that the two exposure operations use the same slit aperture orientation). Let the shifting distance of the two exposed areas be $\delta$. There are two different conditions for $\delta$. The first condition is $\delta = 0$. The second condition is $\delta \neq 0$. When a laser beam is incident on a double-exposed diffusion dot with $\delta = 0$, the intensity spectrum of the scattered light is similar to that of a single-exposed diffusion dot, and it does not have interference fringes. When a laser beam is incident on a double-exposed diffusion dot with $\delta \neq 0$, the intensity spectrum of the scattered light contains several interference fringes caused by the phenomenon of Young's interference of two apertures. This characteristic can be regarded as artificial speckle photography. Because the interference fringes show the orientation information of $\delta$ only, and show no sense information of $\delta$, a double-exposed diffusion dot with $\delta$ and that with $-\delta$ create the same interference fringes.

When a single-exposed pattern and a double-exposed pattern are composed of 2D diffusion dots created with the same slit aperture orientation arrangement, there are three different features for them. (1) Their intensity spectra for the double-exposed pattern may contain interference fringes, but those for the single-exposed pattern do not always contain interference fringes. The spectra can be checked by laser beams. (2) There is a hazy image (caused by the contrast of local areas with $\delta = 0$ and $\delta \neq 0$) on the double-exposed pattern for a viewer looking from a direction nearly parallel to the pattern plane, but there is always no image on the single-exposed pattern for a viewer to see from any direction. This phenomenon can be checked by the naked eye. (3) Their speckle arrangements are different. Speckle arrangements can be checked by an optical microscope.

3. Experiment

All the patterns composed of 2D diffusion dots in this section were created by the same setup shown in Fig. 1. A 10 mW HeCd laser with the wavelength of 442 nm was used as the light source of the setup. The imaging lens was a lens set (XR Heligon) manufactured by Rodenstock, Germany, and had a diameter of 7 cm. The size of the illuminated area of the ground glass surface was photoreduced with $M = 1/5$ to form the diffusion dot. The size of the slit aperture for the mask M2 was approximately 7 cm × 1 cm, and the centers of the slit aperture and the imaging lens coincided. Each pattern was created on a Shipley 1813 photoresist plate with a thickness of 3 mm (the photoresist thickness was 1.5 μm) [9], and the exposure time for every diffusion dot is 10 s. Each exposed photoresist plate was developed in a Shipley 303A developer solution for 8 s. The developer solution was mixed with 150 cc pure water and 30 cc developer.

Figure 3 shows the slit aperture orientation arrangement for a fractal pattern used to create all diffusion patterns in this section. The size of diffusion dots was always 100 μm × 100 μm in this section. The image in Fig. 3 contained 60 × 60 dots, so the size of a diffusion pattern created by the slit aperture orientation arrangement was 6 mm × 6 mm.

Figure 4 shows the different appearance of a single-exposed pattern created on a photoresist plate for the same light source with the same incident angle (the angle between the perpendicular line of the photoresist plate and the progress direction of the incident light) but different incident directions (the progress direction of the incident light was changed). Figure 4 discloses that a pattern composed of 2D diffusion dots can really show different appearance for different illuminating conditions. Figure 5 shows the speckles of the single-exposed pattern inspected by an optical microscope.

Figure 6 shows a double-exposed pattern created on a photoresist plate. The position shifting distance for this double-exposed pattern was $\delta = 0$ μm or $\delta = 10$ μm along the $y$ axis. The appearance of the double-exposed pattern in Fig. 6 was always nearly the same as that of the single-exposed pattern in Fig. 5 when the same illuminating and viewing conditions were used. Figure 7 shows the designed local areas with $\delta = 0$ μm and $\delta = 10$ μm (the area with a letter “E”) for the double-exposed pattern. Figure 8 shows the hazy image “E” on the double-exposed pattern. Figure 9 shows the speckles of the double-exposed pattern inspected by an optical microscope. Figure 10 shows the intensity spectra for three different corresponding position pairs on the patterns in Figs. 5 and 6. The spectra for the intensity of the single-exposed pattern in Fig. 5 did not always have interference fringes, whereas the spectra for the intensity of the double-exposed pattern in Fig. 6 had interference fringes (for the local areas with $\delta = 10$ μm only).

4. Discussion

The antcounterfeiting capacity of diffusion patterns composed of 2D diffusion dots can be classified into
three levels. The first level is to check the dynamic images shown by diffusion patterns. The checking work is fastest, but the anticounterfeiting capacity is weakest (for the checking belonging to quality comparisons). The second level is to check the intensity spectra of the different local areas on diffusion patterns. The checking work is slow, but the anticounterfeiting capacity is strong (for different local areas being able to be double exposed with different \( \delta \) values). The third level is to check the speckle arrangements in diffusion dots. The checking work is very slow, but the anticounterfeiting capacity is very strong (for speckles in diffusion dots being created randomly and for counterfeiting speckles being almost impossible).

Exposing a hologram with energy (per square centimeter) in the linear range of the H–D curve for the photosensitive holographic plates makes the hologram able to accurately record the gray levels of the surface of an object [11], but exposing diffusion dots with energy in the linear range of the H–D curve is not necessary. The reasons are that diffusion dots show different gray levels with different slit aperture orientations and that they are all exposed with the same energy. When the upper limitation of the energy to expose a hologram with a more realistic displaying capacity is \( E \), the energy to expose diffusion dots with a higher diffusion capacity should be larger than \( E \) (even \( 2E \) can be used).

The resolution limitation of diffusion dots is dominated by the sizes of the speckles in the dots. The 1D...
characteristic size of the speckles in a diffusion dot recorded by a 1D slit aperture is approximately $\lambda d/\omega$ [12], where $\omega$ is the width (the shorter dimension) of the slit aperture. Because the speckle phenomenon for a diffusion dot makes the dot contain interlacing bright and dark spots, the size of the diffusion dot must be at least several times larger than the characteristic size of the speckles to avoid no bright spot in a diffusion dot. Therefore diffusion dots should usually not be smaller than $10 \mu m \times 10 \mu m$.

The techniques for showing dynamic images can show stereo effects or multiple images too. Diffusion dots can show the stereo effects of an object by diffracting several images to different directions, and the diffracted images correspond to different prospective views of the object. A diffusion dot contains very many different elementary gratings, and a grating dot contains only a grating; thus the direction range of the light diffracted by a diffusion dot is much wider than that of the light diffracted by a grating dot. Therefore to allow the two eyes of a viewer to see two corresponding views simultaneously to make a stereo effect is not always easy. So the ability to show stereo effects is not excellent for a pattern composed of diffusion dots (compared to a grating-dot pattern), whereas the ability to show multiple images is excellent for a pattern composed of diffusion dots because the images can be seen independently by allowing
their corresponding slit aperture orientations to have large deviations.

5. Conclusion
We have proposed a new type of diffusion pattern. The proposed patterns are composed of 2D diffusion dots. By changing the orientation of the slit aperture on a mask covered on the imaging lens, the diffusion dots can have different intensity spectra for the same incident light beam. Therefore the diffusion dots created by the same slit aperture orientation show the same brightness, and the diffusion dots created by different slit aperture orientations show different brightness for the same illuminating and viewing conditions. Therefore a pattern composed of 2D diffusion dots can show dynamic images by changing its illuminating or viewing conditions. By applying the double-exposure technique to the diffusion dots of a pattern, the pattern not only can show dynamic effects but also can possess hidden features for identifying the pattern.

This work was supported in part by the National Science Council of the Republic of China (grant NSC 95-2212-E-262-006).

References