Generation and optical display of a binary-sampled phase-only hologram

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Past research has demonstrated that a phase-only hologram can be obtained by down-sampling the intensity image of the object scene prior to the generation of the hologram. In this Letter, we extend the method to the generation of binary phase-only holograms. A hologram derived with our proposed method is referred to as a binary-sampled phase-only hologram (BSPOH). Being different from the parent scheme, we have adopted an off-axis configuration in the generation of the BSPOH to avoid the quantization noise, the zeroth-order light, and the conjugate lights. An experimental evaluation reveals that the reconstructed image of the BSPOH is of good quality, and only contains slight amount of noise.

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In the first part of the Letter, we provide an outline on the background related to our proposed method. The exploration of viable methods for generating binary phase-only holograms (POHs) has been conducted for over half a century since the pioneering works of Lohmann[1] in the sixties. The long-term research momentum is driven by the practical reason that it is easier to print binary POHs (through laser lithography or other similar techniques) than a continuous-tone POH. In addition, a binary POH can be displayed with a single, bi-level spatial light modulator (SLM) such as a digital micro-mirror device. From a practical point of view, a single SLM display system is more compact and economical than the dual SLM setup that is often employed in the display of a complex hologram (see the method reported in Ref. [2]). However, generating a binary POH is a tedious process. Popular approaches, which include but are not limited to those in Refs. [3–5], are mostly based on iterative means, with which the hologram pixel is progressively adjusted via multiple rounds of iterations until the reconstructed image is similar to the target image. The computation time is lengthy, especially for large holograms. Non-iterative methods for generating POHs based on random phase-noise injection[6], complex modulation[7], and error diffusion[8,9] have been developed in recent years. The random phase-noise method, commonly known as one-step phase retrieval (OSPR), derives a POH by adding a phase disturbance to each pixel of the source image prior to the generation of the hologram. The addition of the noise effectuates a diffuser that results in a more or less constant-magnitude hologram, so that only the phase component of the hologram alone will be sufficient to reconstruct the source image. On the downside, a POH obtained with the OSPR method is contaminated with noise upon reconstruction. The complex modulation method is capable of generating a POH with an excellent reconstructed image. However, an optical filter is required to extract the correct component from the optical waves diffracted from the hologram, hence increasing the complexity of the optical system. The error diffusion method also results in a high-quality reconstructed image, and it also provides an additional advantage for embedding a large amount of data into the POH[10]. On the downside, the diffraction efficiency is weak, and a brighter illumination is needed. Besides, error diffusion is a recursive process and the computation time is longer than the OSPR or the complex modulation techniques. Although this problem can be reduced with localized error diffusion[11], the reconstructed image is blurred and an optical filter is involved. Recently, Tsang *et al.* proposed a so-called sampled POH (SPOH)[12], whereby the source image is down-sampled with a grid-cross lattice and converted into a POH. Further enhancement is made by including the locations of the edge points into the sampling lattice to preserve the continuity of the edge patterns in the reconstructed image[13]. The method is fast and the reconstructed image of the SPOH is bright and clear. In this Letter, we propose a method to generate binary POHs based on the SPOH technique. Intuitively, it is possible to convert an SPOH into a binary form simply by quantizing the pixel into a bi-level representation. However, as we shall show in later on in this Letter, a binary POH derived with this straightforward approach will result in reconstructed image that is severely contaminated with quantization noise, the zeroth-order light, and the conjugate lights. Our proposed method can overcome these problems. For the sake of clarity, we shall outline the principles of generating an SPOH next. After that, we shall demonstrate the shortcoming of directly binarizing an SPOH through sign thresholding. Subsequently, our proposed method for

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generating a binary SPOH will be presented, and evaluated with optical reconstruction.

We shall now outline the principles of generating the SPOH that is reported in Refs. [12,13]. The process can be divided into three stages, as illustrated in Fig. 1, and explained as follows.

In the first stage, the source image is assumed to be a three-dimensional surface with the intensity and depth of each pixel (i.e., the axial distance from the pixel to the hologram plane) represented by $I(x, y)$ and $D(x, y)$, respectively. The intensity image is down-sampled with a grid-cross lattice $S(x, y)$, resulting in a down-sampled image $I_d(x, y)$, which is given by

$$I_d(x, y) = I(x, y) \times S(x, y). \tag{1}$$

The down-sampling lattice $S(x, y)$ is a union of 4 sub-lattices and can be expressed as

$$S(x, y) = S_0(x, y)\ S_1(x, y)\ S_2(x, y)\ S_3(x, y), \tag{2}$$

where

$$S_0(x, y) = \begin{cases} 1 & (x \bmod M = 0) \vee (y \bmod M = 0) \\ 0 & \text{otherwise} \end{cases}, \tag{3}$$

$$S_1(x, y) = \begin{cases} 1 & (x \bmod M = y \bmod M) \\ 0 & \text{otherwise} \end{cases}, \tag{4}$$

$$S_2(x, y) = \begin{cases} 1 & [(x \bmod M) = M - 1 - (y \bmod M)] \\ 0 & \text{otherwise} \end{cases}, \tag{5}$$

and $S_3(x, y)$ are the locations of the edge points of $I(x, y)$; otherwise, values of "1" and "0" are assigned. The factor M is the down-sampling factor. In Eqs. (3)–(5), the expression "mod" is the modulo-operator, and in Eq. (3), $\vee$ is the logic "OR" operation. The sub-lattices $S_k(x, y)|_{0 \le k < 3}$ of a small canvas are shown in Figs. 2(a)–2(d), with the sampled points highlighted in white. The sample points in the sub-lattice $S_3(x, y)$ are located at the edges of the intensity image $I(x, y)$, so that the continuity of the edge patterns can be preserved.

In the second stage, the down-sampled intensity image, together with the depth map, is converted into a Fresnel hologram as follows:

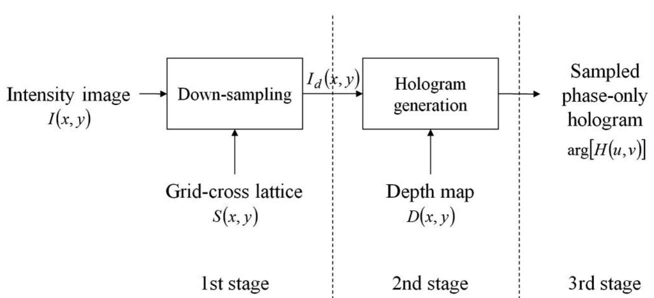

Fig. 1. Process for generating an SPOH.

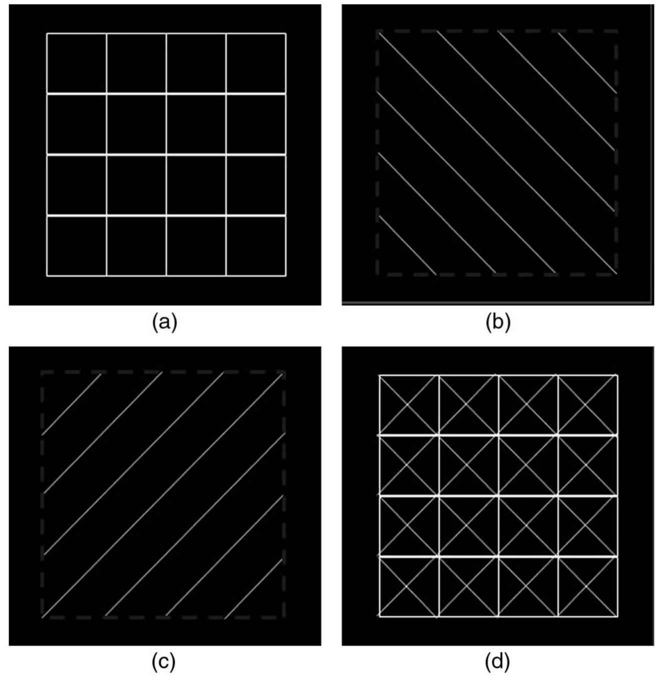

Fig. 2. (a) Sub-lattice $S_0(x, y)$. (b) Sub-lattice $S_1(x, y)$. (c) Sub-lattice $S_2(x, y)$. (d) Down-sampling lattice $S(x, y)$.

$$H(u, v) = \sum_{m=0}^{X} \sum_{n=0}^{Y} I(m, n) \exp\left[\frac{i2\pi}{\lambda} r_{u;v;m;n}\right], \tag{6}$$

where X and Y are the horizontal extent of the hologram, δ is the pixel size of the hologram, $I(m, n)$ is the source image, λ is the wavelength of the optical beam, and $r_{u;v;m;n} = \sqrt{(u-m)^2\delta^2 + (v-n)^2\delta^2 + D^2(m, n)}$.

Finally, in the third stage, the phase component $\arg[H(u, v)]$ of the complex hologram is extracted to be the SPOH.

Now we shall describe our proposed method for generating a binary-sampled POH (BSPOH). An SPOH can be converted into a binary form by quantizing the value of each pixel into 2 levels as follows:

$$H_B(u, v) = \begin{cases} 0 & 0 \le \arg[H(u, v)] < \pi \\ \pi & \text{otherwise} \end{cases}. \tag{7}$$

However, this straightforward approach will lead to heavy degradation of the reconstructed image due to the overlapping of the quantization noise, the zeroth-order light, and the conjugate lights. To overcome this problem, we propose to convert the complex hologram $H(u, v)$ into an off-axis hologram $H_{oa}(u, v)$ by multiplying it with an inclined incident plane wave. Mathematically, the off-axis hologram is given by

$$H_{oa}(u, v) = H(u, v) \times R(v), \tag{8}$$

where $R(v) = \exp[\frac{i2\pi}{\lambda} v \sin(\Phi)]$, and Φ is the angle of inclination of the reference plane wave along the vertical direction. Subsequently, $H_{oa}(u, v)$ is converted into a BSPOH $G_B(u, v)$ as follows:

$$G_B(u,v) = \begin{cases} 0 & 0 \le \arg[H_{\mathrm{oa}}(u,v)] < \pi \\ \pi & \text{otherwise} \end{cases}. \tag{9}$$

When the BSPOH $G_B(u,v)$ is illuminated with a plane wave, the reconstructed image will be projected along a slant direction at an angle Φ, as shown in Fig. 3. The quantization noise, the zeroth-order light, and the conjugate lights will be mainly formed along the axial direction, which is non-overlapping with the reconstructed image.

We shall now present the experimental results of our proposed method. A source image "Star" of dimension 1024×1024 as shown in Fig. 4(a) is employed to demonstrate our proposed method. To begin with, the intensity $I(x,y)$ of the source image is down-sampled with the grid-cross lattice $S(x,y)$ based on a down-sampling factor $M = 12$, and converted into a hologram with Eq. (6). The source image is assumed to be parallel to, and at an axial distance of 0.3 m from, the hologram. The optical settings are listed in Table 1.

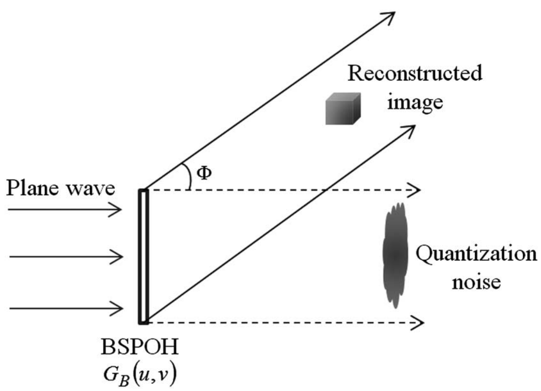

Fig. 3. Reconstructed image of the proposed BSPOH along a slant direction, and the quantization noise along the axial direction.

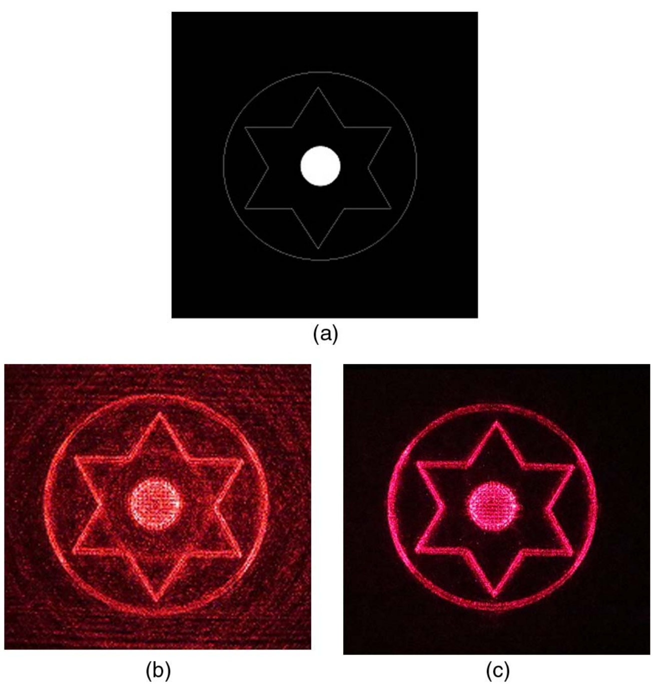

Fig. 4. (a) Intensity image $I(x,y)$. (b) Optical reconstructed image of the binarized SPOH obtained by directly quantizing the hologram into a bi-level representation. (c) Optical reconstructed image of the off-axis BSPOH that is generated with our proposed method.

An SPOH is obtained by preserving only the phase component of the hologram, and Eq. (7) is applied to quantize the image into a bi-level representation. The binarized hologram is displayed with the LC-R1080 reflective SLM from HOLOEYE, which has a display area of 1920×1080, and is shown in Fig. 4(b). We observe that the image is heavily contaminated with noise. Next, we prepare a BSPOH with our proposed method based on an off-axis reference plane wave of angle $\Phi = 1.2°$. The off-axis BSPOH image is displayed on the SLM, and the result is shown in Fig. 4(c). It can be seen that the reconstructed image is of good quality, and separated from the noise that appears in a separate display area.

Next, we evaluate the correlation score between the reconstructed images of the off-axis BSPOH $G_B(u,v)_{\mathrm{Star}}$ and the original off-axis SPOH $H_{\mathrm{oa}}(u,v)|_{\mathrm{Star}}$, and the diffraction efficiency of the off-axis BSPOH. For the correlation score, the measurement is made with the reconstructed images restricted to the area of the original image. For the diffraction efficiency, we calculate the ratio of the signal energy that is within the area of the reconstructed image (i.e., the 1024×1024 area covered by the original image) to the signal energy of the entire reconstruction area (i.e., the 2048×2048 area covered by the hologram). The correlation score and the diffraction efficiency of the BSPOH $G_B(u,v)_{\mathrm{Star}}$ are 0.8 and 71%, respectively, reflecting a favorable preservation of the information represented in the BSPOH and moderate diffraction efficiency.

Similar treatment is given to the 1024×1024 image "Eye" in Fig. 5(a) and the 1024×2048 image "Squares" in Fig. 5(b). An off-axis SPOH is generated based on $\Phi = 1.5°$, and converted into a BSPOH with Eq. (9) for each image. The numerical reconstructed images of the off-axis SPOHs (i.e., $H_{\mathrm{oa}}(u,v)_{\mathrm{Eye}}$ and $H_{\mathrm{oa}}(u,v)_{\mathrm{Squares}}$) and the BSPOHs ($G_B(u,v)_{\mathrm{Eye}}$ and $G_B(u,v)_{\mathrm{Squares}}$) of these 2 images are shown in Figs. 6(a)–6(d). A comparison between the reconstructed images of the POHs before and after binarization (i.e., the application of Eq. (9)) shows that they are similar, reflecting that useful information is preserved. The correlation score (with reference to

Table 1. Optical Settings in Generating the Complex Hologram

Size of Hologram	2048×2048
Pixel Size of Hologram and Source Image	8.1 μm × 8.1 μm
Wavelength of Optical Beam	632.8 nm

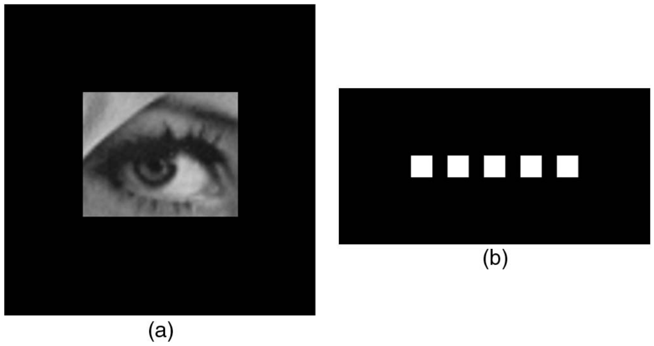

Fig. 5. (a) Intensity image "Eye." (b) Intensity image "Squares."

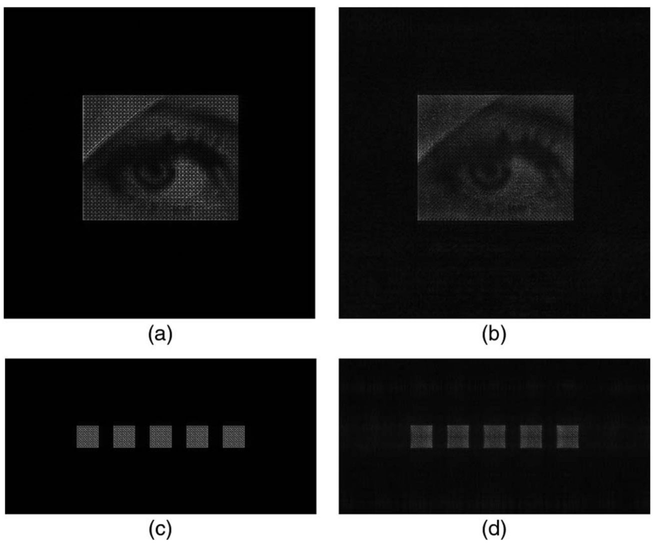

Fig. 6. (a) Numerical reconstructed image of the off-axis SPOH $H_{\mathrm{oa}}(u,v)_{\mathrm{Eye}}$ of the image "Eye." (b) Numerical reconstructed image of the off-axis BSPOH $G_B(u,v)_{\mathrm{Eye}}$ of the image "Eye." (c) Numerical reconstructed image of the off-axis SPOH $H_{\mathrm{oa}}(u,v)_{\mathrm{Squares}}$ of the image "Squares." (d) Numerical reconstructed image of the off-axis BSPOH $G_B(u,v)_{\mathrm{Squares}}$ of the image "Squares."

$H_{\mathrm{oa}}(u,v)_{\mathrm{Eye}}$) and the diffraction efficiency of $G_B(u,v)_{\mathrm{Eye}}$ are 0.78 and 78%. The correlation score (with reference to $H_{\mathrm{oa}}(u,v)_{\mathrm{Squares}}$) and the diffraction efficiency of $G_B(u,v)_{\mathrm{Squares}}$ are 0.75 and 61%. These results are consistent with the previous example, reflecting favorable fidelity and diffraction efficiency in the reconstructed images of the BSPOHs in both cases.

Past research has demonstrated that a POH can be obtained by first down-sampling the intensity of the source image with a grid-cross lattice, and preserving only the phase component of its hologram. A hologram generated with such means is referred to as an SPOH. In this Letter, we have extended this approach to the generation of a binary-sampled phase-only hologram. We have shown that if an SPOH is binarized through direct quantization into a bi-level representation, the reconstructed image will be heavily immersed in quantization noise. In view of this, we have proposed to multiply the complex Fresnel hologram of the down-sampled source image with an off-axis plane wave, and extract the phase component of the product. Subsequently, the phase component is binarized to obtain the BSPOH. The experimental results reflect that the reconstructed image of a BSPOH derived with the proposed method is of favorable quality, and is separated from the quantization noise.

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