Improvement of Image Quality of Wide-Angle Holographic Display Using a Non-Periodic Photon Sieve

Shunki Sasaki[1] and Yasuhiro Takaki[1]

s209409u@st.go.tuat.ac.jp
[1]Tokyo University of Agriculture and Technology, 2-24-16 Naka-cho, Koganei, Tokyo 184-8588, Japan
Keywords: Holography, photon sieve, viewing zone angle

ABSTRACT

This study improves the image quality of the reconstructed images generated through holographic techniques using a non-periodic photon sieve, which provides a wide viewing zone angle. We developed the optimization technique based on the Gerchberg–Saxton algorithm to calculate the phase distribution displayed on the phase-only spatial light modulator.

1 Introduction

Recently, a holographic display technique using a non-periodic photon sieve has been proposed, dramatically increasing the viewing zone angle and the screen size of holographic displays [1]. Conventional holographic techniques require reducing the pixel pitch of the spatial light modulator (SLM) to enlarge the viewing zone and increasing the resolution of the SLM to enlarge the screen size [2, 3]. However, introducing a non-periodic photon sieve onto a phase-only SLM eliminates the trade-off between the viewing zone angle and screen size, which has hindered the development of practical holographic displays for a long time. The viewing zone angle of 30° was demonstrated using a phase-only SLM with a pixel pitch of 36 μm [1]. Despite this achievement, the reconstructed images suffered from poor quality, in addition to the darkness. This study proposes a phase optimization technique based on the Gerchberg–Saxton algorithm [4] to improve the image quality of the holographic display using a nonperiodic photon sieve.

2 Theory

We briefly explain the holographic display technique using a non-periodic photon sieve [1]. The conventional holographic display techniques have used SLMs having periodically aligned pixels. As shown in Fig. 1(a), the periodic pixel structure caused the periodic generation of higher-order diffraction lights to limit the viewing zone angle. However, introducing a non-periodic photon sieve, as shown in Fig. 1(b), suppresses the generation of higher-order reconstructed images to enlarge the viewing zone. In this approach, each aperture in the photon sieve corresponds to an individual pixel of the SLM, with the positions of the apertures randomly determined. The diameter of these apertures determines the divergence of light, i.e., the viewing zone angle. Decreasing the aperture size allows for an increase in the viewing zone angle. A simple calculation was performed to determine the phase distribution displayed on the phase-only SLM by evaluating the distances between points comprising the holographic image and the apertures in the photon sieve. Figure 2(a) shows the reconstructed image obtained through the computer simulation when the pixel pitch and the resolution of the SLM were 8 μm and 128 × 128, respectively. The aperture width was 2 μm. The wavelength of light was 633 nm, and the reconstruction distance was 0.663 mm.

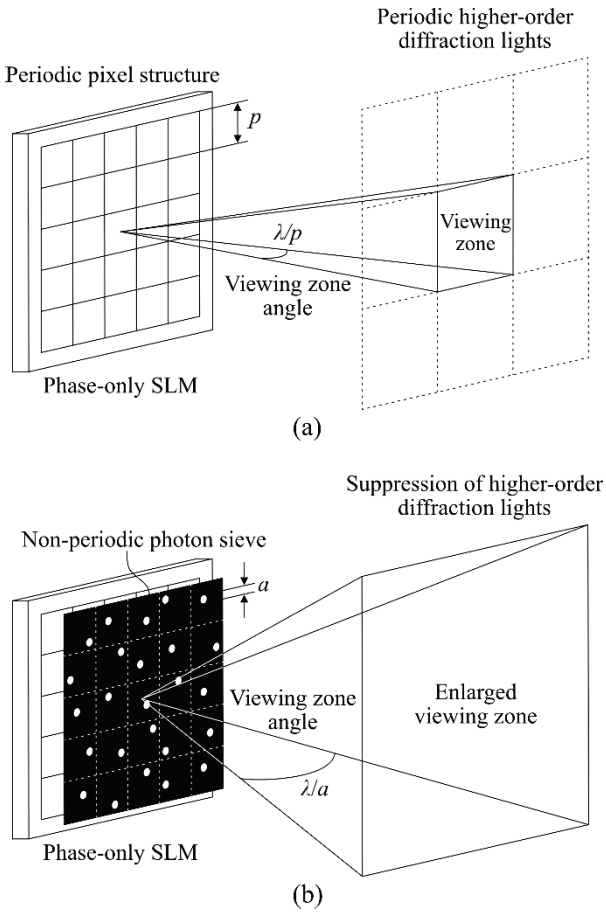


Fig. 1 Holographic display techniques using (a) SLM and (b) SLM with a non-periodic photon sieve. λ is the wavelength of light.

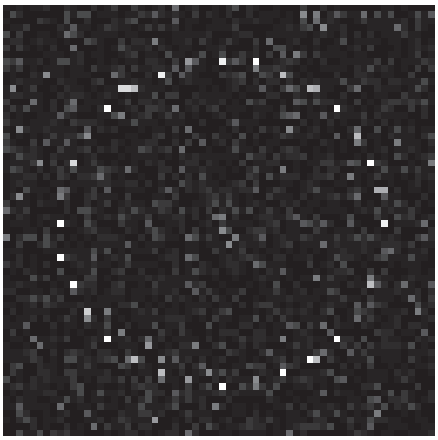


Fig. 2 Holographic image generated using a non-periodic photon sieve (number of modes is 32).

(a)

(b)

Fig. 3 Holographic images for the number of modes is 32 × 32: (a) conventional technique and (b) proposed technique.

The reconstructed images generated using the non-periodic photon sieve are considered a collection of modes, representing points with controlled intensities. The number of modes is proportional to the contrast factor, which is the ratio of the intensity of a single peak image to the average value of background noises caused by the randomness of the photon sieve [1]. In the case shown in Fig. 2, the calculated contract factor was 708, corresponding to 32 modes. However, the image quality degraded when the number of modes was increased to 1,024, as shown in Figure 3(a), where four characters were drawn on equally spaced 32 × 32 modes.

Herein, the image quality of the holographic images generated using the photon sieve is improved by optimizing the phase distribution displayed on the phase-only SLM. Figure 4 shows the proposed phase optimization technique based on the Gerchberg–Saxton algorithm [3]. It involves iterative diffraction and inverse diffraction calculations between the hologram and diffraction planes. On the hologram plane, the amplitude distribution is replaced by the transmittance of the non-periodic photon sieve. Then, the phases at the apertures are calculated to obtain the phase distribution displayed on the phase-only SLM. On the diffraction plane, the amplitudes at the modes are replaced by the target amplitudes, while the remaining distribution remains unchanged. Through this iterative calculation, the phase distribution displayed on the SLM is obtained, approximately satisfying the constraints on both the hologram and diffraction planes.

This study uses the angular spectrum (AS) method [5] for the diffraction calculation, although a previous study used the Fresnel approximation [1]. As shown in Fig. 5(a), when using the AS method, the size of the diffraction image remains constant depending on the diffraction distance, as does the pitch of the modes. In contrast, when the Fresnel approximation is used, as shown in Fig. 5(b), the size of the diffraction image and the pitch of the modes change linearly with the diffraction distance.

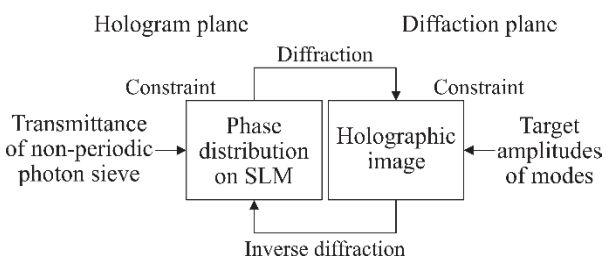


Fig. 4 Phase optimization algorithm proposed in this study.

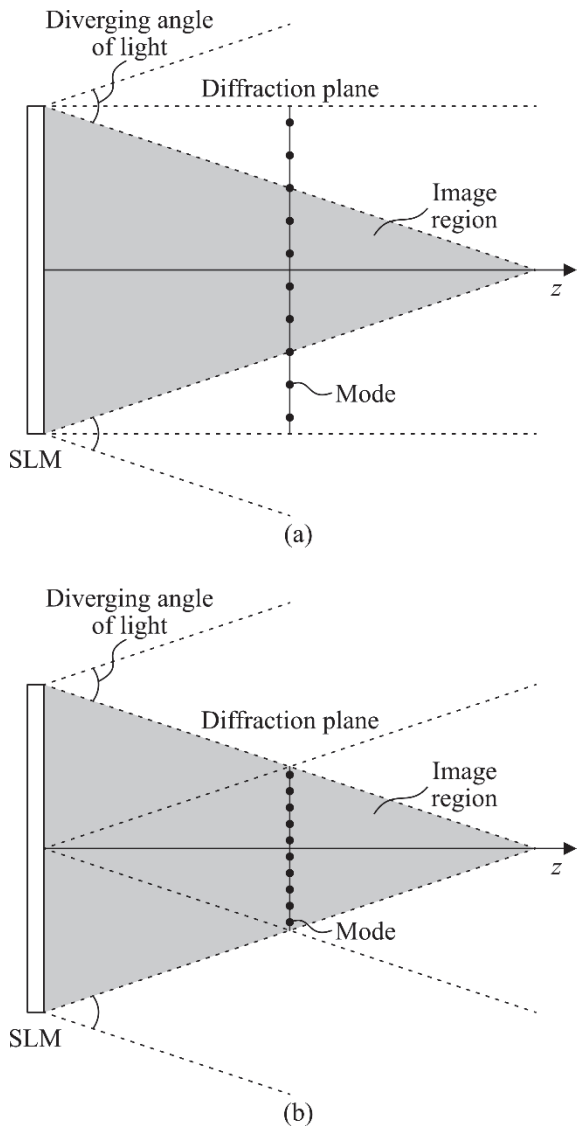


Fig. 5 Diffraction calculations: (a) AS method used in this study and (b) Fresnel approximation used in a previous study [1].

3 Simulation

The proposed technique was verified using computer simulation.

The holographic image shown in Fig. 3(a) was improved using the proposed technique. A total of 100 iterations were performed for phase optimization, resulting in an increased contrast factor of 1,027. The improved holographic image is shown in Fig. 3(b). The peak-signal-to-noise ratio (PSNR) calculated for the mode points reached 16.6 dB, surpassing the 13.1 dB achieved by a previous technique.

Next, the resolution of the phase-only SLM was increased to 256 × 256 to explore the potential increase in the number of modes. The reconstruction distance was 1.33 mm. The calculated contrast factors for the previous and the proposed techniques were 2,870 and 3,841, respectively. Figure 6 shows the reconstructed images when the number of modes was increased to 64 × 64. These results indicate that the proposed technique effectively improved the image quality of the holographic images. The PSNRs for the holographic images obtained using the previous and proposed techniques were 13.1 dB and 15.9 dB, respectively.

Finally, the resolution of the SLM was further increased to 512 × 512. The reconstruction distance was 2.65 mm. Concurrently, the number of modes was increased to 128 × 128, enabling the display of the grayscale images. As a result, the contrast factors for the previous and proposed techniques reached 11,350 and 14,248, respectively. The obtained holographic images are shown in Fig. 7. The PSNRs of these images were 13.2 dB and 18.9 dB, using the previous and proposed techniques, respectively. These results also show the effectiveness of the proposed technique.

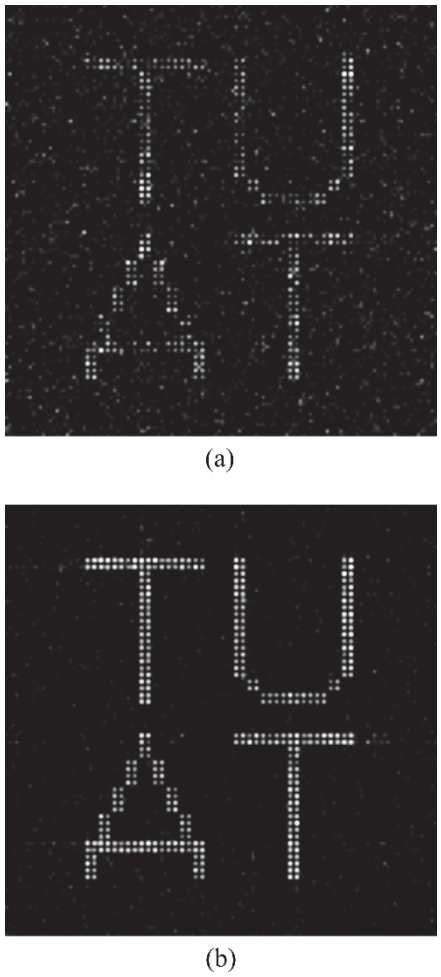
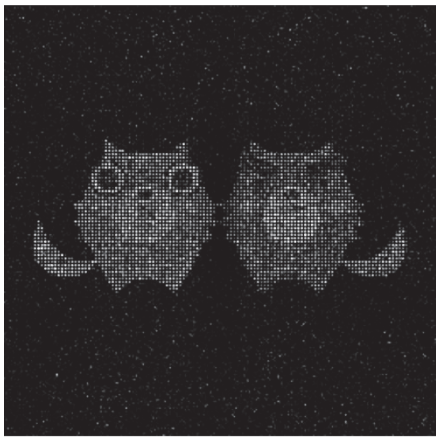


Fig. 6 Simulation results for holographic image consisted of 64 × 64 modes: (a) previous technique and (b) proposed technique.

(a)



(b)

Fig. 7 Simulation results for holographic image consisted of 128 × 128 modes: (a) previous technique and (b) proposed technique.

4 Summary

Herein, the image quality of the holographic display technique using a non-periodic photon sieve was improved. To achieve this, the iterative phase optimization technique was developed based on the Gerchberg–Saxton algorithm. The computer simulation showed that the PSNR was improved from 13.1 dB to 15.9 dB for the holographic image consisting of 64 × 64 modes, and the PSNR also improved from 13.2 dB to 18.9 dB for the 128 × 128 modes. Consequently, the proposed technique was verified through computer simulation. In future work, we will experimentally confirm the effectiveness of the proposed technique.

References

[1] J. Park, K. Lee, and Y. Park, “Ultrathin wide-angle large-area digital 3D holographic display using a non-periodic photon sieve,” Nature Communications, Vol. 10, No. 1, 1304 (2019).

[2] F. Yaras, H. Kang, and L. Onural, “State of the art in Holographic displays: A survey,” Journal of Display Technology, Vol. 6, No. 10, 443–454 (2010).

[3] A. W. Lohmann, R. G. Dorsch, D. Mendlovic, C. Ferreira, and Z. Zalevsky, “Space–bandwidth product of optical signals and systems,” Journal of the Optical Society of America A, Vol. 13, No. 3, 470–473 (1996).

[4] R. W. Gerchberg, “A practical algorithm for the determination of phase from image and diffraction plane pictures,” Optik, Vol. 35, No. 2, 237–246 (1972).

[5] K. Matsushima, H. Schimmel, and F. Wyrowski, “Fast calculation method for optical diffraction on tilted planes by use of the angular spectrum of plane waves,” Journal of the Optical Society of America A, Vol. 20, No. 9, 1755–1762 (2003).