Adjustable liquid aperture to eliminate undesirable light in holographic projection

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Abstract: In this paper, we propose an adjustable liquid aperture to eliminate the undesirable light in a holographic projection. The aperture is based on hydrodynamic actuation. A chamber is formed with a cylindrical tube. A black droplet is filled in the sidewall of the cylinder tube and the outside space is the transparent oil which is immiscible with the black droplet. An ultrathin glass sheet is attached on the bottom substrate of the device and a black shading film is secured to the central area of the glass sheet. By changing the volume of the black droplet, the black droplet will move to the middle or sidewall due to hydrodynamic actuation, so the device can be used as an adjustable aperture. A divergent spherical wave and a solid lens are used to separate the focus planes of the reconstructed image and diffraction beams induced by the liquid crystal on silicon in the holographic projection. Then the aperture is used to eliminate the diffraction beams by adjusting the size of the liquid aperture and the holographic projection does not have undesirable light.

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1. Introduction

The holographic projection based on the liquid crystal on silicon (LCoS) has attracted much attention due to the remarkable advantages of the LCoS including high integration, large opening ratio and high resolution [1–4]. However, because of the pixelated structure of the LCoS, undesirable light caused by zero-order diffraction beam and high-order reconstructed images exists. Some scholars load converging spherical wave to the phase distribution of the hologram [5–7], then the zero-order noise can be eliminated with an aperture. Moreover, in order to eliminate the high-order reconstructed images, a 4f lens is often needed in the system [6, 8]. So the system without undesirable light is complex. Recently, the liquid optical components such as liquid lens [9–13] and liquid aperture [14–17] have been found wide applications in zoom systems. Usually these liquid components are lighter, smaller and more flexible than the conventional ones. Moreover, they can be reconfigured very quickly. In this paper, we propose an adjustable liquid aperture to eliminate the undesirable light in the holographic projection without a 4f lens. The liquid aperture is based on hydrodynamic actuation. By adjusting the size of the liquid aperture, we can eliminate the zero-order diffraction beam and high-order reconstructed images and the holographic projection does not have undesirable light.

2. Structure and operating principle

The side-view of the proposed liquid aperture and its operating mechanism are depicted in Fig. 1. As shown in Fig. 1(a), the chamber is formed with a cylindrical tube made of PMMA. An ultrathin glass sheet with trapezoidal notch is fabricated on the bottom substrate and a black shading film is secured to the glass sheet. A black droplet is filled in the sidewall and the outside space is the transparent oil which is immiscible with the droplet. Figure 1(b) shows the top view of the device. The bottom chamber is used to connect a pumping syringe through channel 1 and the top chamber is used to connect a pumping through channel 2. When the black droplet is injected into the bottom chamber through channel 1, the droplet will spread on the ultrathin glass sheet of the bottom chamber uniformly due to the interfacial tensions, adsorption and pressure, while the transparent oil flows out through channel 2. In this case, the opening aperture decreases, as shown in Fig. 1(c). When the black droplet injected into the bottom chamber increases, the droplet will further spread on the ultrathin glass sheet of the bottom chamber and the opening aperture decreases accordingly. When the black droplet injected into the bottom chamber reaches a certain amount, the droplet cannot be injected any more and the opening aperture cannot decrease any more due to the balance between pressure, gravity, interfacial tensions and adsorption. By changing the black droplet injected into the chamber, we can adjust the size of the liquid aperture. So the device is adjustable.
To fabricate the proposed liquid aperture, the external diameter of the tube is 13mm and the inside diameter is 11mm. The height of the tube is 8mm. The top and bottom of the tube are tightly covered by the glass substrates using UV331 glue. A 2mm-thick glass sheet with trapezoidal notch (each trapezoidal layer is 0.4mm) is fabricated on the bottom substrate and a black shading film (1.1mm × 1.1mm) is secured to the glass sheet. In our experiment, water dyed with ink is used as the black droplet (the density is 1.15g/cm³) and the surrounding is filled with silicone oil (the density is 0.96g/cm³).

In the holographic projection, the diffraction image is composed of two parts: the diffraction beams caused by pixelated structure of the LCoS and the other is the reconstructed images of the hologram. In order to get a desirable viewing experience, the former needs to be eliminated. The liquid aperture is used to eliminate the undesirable light come from the diffraction beams. We set up a holographic projection including the liquid aperture, as shown in Fig. 2. Besides the liquid aperture, the holographic projection consists of a laser, a filter, a collimating lens, a LCoS, a solid lens and a receiving screen. The laser, the filter and the collimating lens are used to generate a collimated light. The solid lens is placed behind the LCoS. The liquid aperture locates between the solid lens and the receiving screen.

In order to separate the focus planes of reconstructed image and the high-order diffraction beams, a divergent spherical wave is loaded on the phase distribution of the hologram, and its phase can be expressed as follows [5]:
\[ \phi_k = -\frac{k}{2r} (x^2 + y^2), \]  

(1)

where \( k = 2\pi / \lambda \), \( \lambda \) is the wavelength of the collimated light, \( r \) is the radius of the divergent spherical wave. As the divergent spherical wave acts on active area of the LCoS, the focus positions of the high-order lights and zero-order light remain unchanged in the back focal plane of the solid lens, while the focus positions of multi-order reconstructed images move backward.

The principle of the holographic projection is shown in Fig. 3. \( d_1 \) is the distance between the LCoS and solid lens, \( d_2 \) is the distance between the solid lens and the aperture (the focal length of the solid lens is \( d_2 \)), and the distance between the solid lens and the screen is \( d_3 \). According to the lens’ imaging equation, \( d_3 \) can be expressed as follows:

\[ \frac{1}{r + d_1} + \frac{1}{d_3} = \frac{1}{d_2}. \]  

(2)

So when \( r \) changes, the position of the receiving screen changes accordingly, and the size of the reconstructed image on the receiving screen can be expressed as follows [11]:

\[ H = \frac{f \lambda d_3}{p(r + d_1)}, \]  

(3)

where \( H \) is the size of the reconstructed image, \( f \) is the focal length of the solid lens, and \( p \) is the pixel size of the LCoS. When light passes through the liquid aperture, zero-order diffraction beams can be eliminated by the black shading film of the liquid aperture, and high-order diffraction image can be eliminated by adjusting the size of the liquid aperture.

3. Experiments and results

The size of the liquid aperture can be adjusted by changing the black droplet injected into the chamber, as shown in Fig. 4, where \( D \) is the diameter of the opening aperture. In the initial state, the black droplet tightly attaches to the side wall due to the high interfacial tension between the sidewalls, as shown in Fig. 4(a). When the black droplet is injected into the bottom chamber through channel 1, the droplet spreads on the ultrathin glass sheet of the bottom chamber uniformly, so the opening aperture decreases. With the increasing of the black droplet injected into the chamber, the opening aperture decreases gradually, as shown in Figs. 4(b)-4(f). The adjustable aperture is based on hydrodynamic actuation. As the diffusion of the liquid is not entirely uniform, the edge of the liquid aperture is not sharp. In the experiment, the camera is fixed above the liquid device, so the shape of the annular portion seems to be not radial in this angle. We do an experiment every 20 minutes and Fig. 5 shows the relationship between the volume of the black droplet and the diameter of opening aperture, where the red line represents the first experiment, and the green line and the blue line represent the second and the third experiments respectively. From the result we can see
that the device can be used repeatably. When the light is used to illuminate the device, light can only pass the annular portion, while it cannot pass the center and the peripheral portion due to the shading of the black film and the absorption caused by the droplet, respectively.

![Fig. 4. Changes of the aperture. (a) \(D = 8.4\)mm; (b) \(D = 7.5\)mm; (c) \(D = 7.0\)mm; (d) \(D = 6.5\)mm; (e) \(D = 6.0\)mm; (f) \(D = 5.4\)mm.](image)

In the holographic projection, a laser diode (\(\lambda = 471\)nm) is used as the light source to irradiate the LCoS, the LCoS we use is reflective, and its pixel number and pixel pitch are 1920 \times 1080 and 8\(\mu\)m, respectively. The solid lens with focal length of 30cm locates 15cm behind the LCoS, and the aperture is fixed behind the solid lens at 30cm. We put the corresponding parameters into Eqs. (2)-(3) and we can get the size and the position of the reconstructed images. We use a “car” as the object and record its reconstructed images using the system without the aperture, and the results are shown in Fig. 6. Figure 6(a) is the original object, and Fig. 6(b) is the reconstructed image with undesirable light. Due to the pixelated structure of the SLM, the image energy in the zero order position is the highest. So we displace the first order images to the zero order spot to improve the quality of the reconstructed images. In order to move the reconstructed image to the center, a digital blazed grating is loaded to the hologram and the result is shown in Fig. 6(c). Figure 7 shows the reconstructed images using the system with the liquid aperture. The results show that the zero-order diffraction beam is eliminated. In order to illustrate the functionality of the aperture, we change the size of the reconstructed images by changing \(r\). From the results we
can see that when the size of the reconstructed images changes, high-order reconstructed images can also be eliminated by adjusting the size of the liquid aperture.

![Images](image1)

**Fig. 6.** (a) Original object, (b) the reconstructed images with undesired light and (c) the reconstructed image which moves to the center.

![Images](image2)

**Fig. 7.** Reconstructed images using the system with the liquid aperture. (a) $D = 8.5\text{mm}$; (b) $D = 7.4\text{mm}$; (c) $D = 6.5\text{mm}$; (d) $D = 6.3\text{mm}$; (e) $D = 6.1\text{mm}$; (f) $D = 5.8\text{mm}$.

Compared to the traditional apertures, the proposed liquid aperture has some advantages. For example, when the light is used to illuminate the device, the light can only pass the annular portion, while it cannot pass the center and the peripheral portion due to the shading of the black film and the absorption caused by the droplet, respectively. So it can be used to eliminate the zero-order diffraction beam and high-order reconstructed images easily, and the cost of the system is low and the structure of the system is simple. Besides, the size of the liquid aperture can be adjusted conveniently and it has wide application in the holographic zoom system [18]. As shown in Fig. 8, we use the liquid aperture in the holographic zoom system. Different from Fig. 2, a liquid lens is used in Fig. 8. By using controlling the radius of the divergent spherical wave and the focal length of the liquid lens, we can change the magnification of the reconstructed image very quickly, while the output plane of the system keeps stationary. By adjusting the size of the aperture, the zero-order diffraction beam and high-order reconstructed images can be eliminated. So the system can realize the zoom function without undesirable light easily. Compared to the proposed zoom system without undesirable light [11], the system using the liquid aperture is simple, which has certain advantages. Moreover, the liquid aperture can also be used in digital cameras and other systems.
However, the liquid aperture still has some unsolved issues. For example, response time measured in our experiment is not fast enough because of the hydrodynamic actuation, as shown in Fig. 9. From Fig. 9 we can see that the response time changes with the aperture size. When the droplet injected into the device increases, the response time increases due to pressure, gravity and interfacial tensions. When the aperture size is ~5mm, the response time is ~340ms. Due to the scattering of the tunable liquid aperture, the result is not very clear. The quality of the reconstructed image may be affected due to the absorption of the device. We have added the relationship between the transmittance and wavelength of the liquid aperture, as shown in Fig. 10. From the results we can see that when light passes through the liquid aperture, ~25% of the energy will lose. The wavelength of the laser we used in the experiment is 471nm. When light passes through the liquid aperture, ~25% of the energy will lose according to Fig. 10. So compared to Fig. 6, the quality of the reconstructed images in Fig. 7 is poor. In our holographic experiment, the aperture is not round enough due to the gravity effect. For this issue, it can be solved by decreasing the size of the device or reducing the density difference between the two liquids. Besides, the response time can be improved further if the inner sidewall of the tube is coated with a hydrophilic layer, because a high interfacial tension between the liquid and inner sidewall can overcome the gravity effect. When the liquid aperture is used in the zoom system, as shown in Fig. 8, the quality of the result will be improved due to the converging action of the zoom lens. In the next work, we will continue to improve our device to make our system better.
4. Conclusion

In this paper, an adjustable liquid aperture to eliminate the undesirable light in the holographic projection is proposed. The liquid aperture is based on hydrodynamic actuation. By adjusting the size of the liquid aperture, we can eliminate the zero-order diffraction beam and high-order reconstructed images and the holographic projection does not have undesirable light.

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