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Color dynamic holographic display with wide viewing angle by improved complex amplitude modulation

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Abstract: An improved method of complex amplitude modulation (CAM) is proposed for color holographic display with a wide viewing angle. Bandlimited random initial phase is introduced to the CAM method, which overcomes the drawbacks brought by a constant initial phase and maintains the advantages of CAM. Modifications in CAM for color display are also explained. Both simulation and experimental results verify that the proposed method can reconstruct color 3D scenes successfully without the time-consuming process for encoding the computer-generated holograms. Compared with the display via traditional CAM, the results exhibit that the proposed method can reconstruct color 3D scenes with a better viewing effect. Because of the display effect improvement and the high calculation speed, this method can be applied to high performance holographic display.

OCIS codes: (090.1760) Computer holography; (090.2870) Holographic display; (090.5694) Real-time holography.

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1. Introduction

Computer generated holography is based on advanced computer technology and the basic principle of wave optics, and it is widely employed in many optical fields. Holographic display, one of significant applications of computer generated holography, can effectively reconstruct desired both two-dimensional (2D) and three-dimensional (3D) images and provide whole depth cue for human eyes, so it is considered as one of most ideal display techniques. Though many scientists have devoted to the research of holographic display and achieved noted developments, there are still some issues to be dealt with. In the display, the computer-generated holograms (CGHs) are loaded on spatial light modulators (SLMs) to acquire the target wavefront, so the features of SLMs have great influence on the display effect and image quality. The characters of SLM modulation are the main limitation [1-2]. A single SLM itself is hardly modulating amplitude and phase simultaneously and independently; however, mathematically, most object wave distribution on hologram plane contains both phase and amplitude information, which indicates that there is information loss in CGH encoding. Phase-only SLMs are the most common ones for holographic display because of its high diffraction efficiency. For instance, kinoform is one of simplest way to encode complex amplitude distribution into phase-only information by treating the amplitude component as constant. Furthermore, the random initial phase on object surfaces introduced in the CGH encoding is a source of calculation speckle [3], which decays the image quality directly.

To solve this problem, two kinds of methods are presented: one is using specific CGH encoding algorithms, and the other is utilizing complex amplitude modulation techniques. Optimization algorithms are proposed for phase retrieval, design of diffraction optical elements, and holographic display. Iteration algorithms (such as Gerchberg-Saxton (GS) algorithm [4], Fienup algorithm [5], Fidoc method [6] and Yang-Gu algorithm [7]) and other optimization algorithms (such as direct binary search [8], and simulated annealing algorithm [9]) are all time consuming, which cause that these algorithms may be hardly employed in real-time display. One-step phase-retrieval method [10] is a compromised method, where high frame rate devices are required, and more CGHs should be calculated for one frame; however, although it can be an effective way for 2D projection, it causes too much computation load to be used in 3D display. Complex amplitude modulation (CAM) by using SLMs and assistant optical systems is an alternative technique to improve the modulation character of the system. The methods encode target complex distribution into CGHs that meets the modulation curve of SLMs, and assistant optical systems ensure that the target distribution is expressed correctly. A number of the approaches have been presented and investigated. The methods with the superposition of two sub-CGHs generate the complex distribution in a simple way [11], while a precisely alignment is necessary in the realization. Superpixel methods combine two or more pixels as one “superpixel” by resampling the wavefront distribution [12-13] or mixing the information with optical deflection element [14-15]. However, the former way leads to internal shift structure in a superpixel, and the later one requires special elements of each individual SLM. Moreover, scholars present the method according to iteration algorithms [16-17], holography [18-19], and other principles [20–25] to modulate the amplitude and the phase of wavefront simultaneously and independently.

Nevertheless, there is a common problem in holographic display with CAM. No matter which kind of method is employed, the initial phase distribution on the object surfaces in the desired scene is neglected or represented by constant function. It suggests that the objects are considered as ones with mirror surface; on the other hand, the random phase is used to simulate the diffuse reflection. As known, mirror surfaces can be observed in a narrow zone, while it is an opposite situation for diffuse surfaces. As a result, choosing a random-free initial phase may be a feasible way to improve the image quality in projection [26-27], but it decreases the viewing angle in 3D display.

In this paper, a bandlimited random initial phase is introduced into the calculation of CGHs in holographic display with CAM. Without utilizing the constant initial phase distribution on object surfaces, one can obtain wider viewing angle in 3D display; meanwhile, a high image quality is achieved because of using the CAM method based on optical holography with filtering system [19]. In order to overcome the disadvantageous by random phase, we pre-calculate the initial phase with limited bandwidth, which is determined by the filtering aperture in the CAM system. In the numerical simulation and the optical experiment, the target images are displayed successfully by the proposed method. The reconstructed results by different methods are compared to demonstrate the benefits of the using limit-bandwidth random initial phase and CAM. By combining CAM method based on optical holography, the time-division system and the proposed method, a color holographic display is realized with larger viewing angle that in the display based on traditional CAM method. Meanwhile a dynamic display is achieved as well. Though a specific CAM method is applied here in our verifications, the proposed method can also be employed into other holographic display systems based on CAM with filtering architecture.

2. The basic principle

2.1 Complex amplitude modulation based on optical holography

There are many sorts of CAM methods that introduce filtering system to filter out redundant information and background noise. The basic principle of them are distinctive, but the similar filtering systems cause the further limitation of the system's bandwidth. Before explaining the principle of the proposed method, a typical CAM method in [19] with filtering architecture is introduced, which is also applied in the verifications for its high image qualities in holographic display. In this method, phase-only optical holography is applied to realize 3D dynamic holographic display with filtering system [19]. The wavefront of a desired scene $O(x,y)$ on holographic plane xoy is calculated according to holographic algorithms [28–32], and it is mapped to phase distribution that can be described as:

$$\Phi(x,y)=\mathbf{exp}\left\{j\beta O_0(x,y)\cos\left[\varphi_0(x,y)-\varphi_r(x,y)\right]\right\}, \tag{1}$$

where $O_0(x,y)$ and $\varphi_o(x,y)$ are the amplitude and the phase of $O(x,y)$ respectively, $\varphi_r(x,y)$ is the reference phase, β is the constant coefficient, and j is imaginary unit. Normally, the reference phase is a tilted phase factor given by $k\left(\sin\theta_x x+\sin\theta_y y\right)$, where k is the wave number, θ_x and θ_y are the tilted angles along two directions. According to the basic feature of Bessel function, the reconstructed wave can be expanded and the first term of it is written as:

$$u_{-1}(x,y)\approx j\beta O_0(x,y)\mathbf{exp}\left[j\varphi_0(x,y)\right]. \tag{2}$$

In order to obtain the information expressed as Eq. (2) in the optical reconstruction, one should filter out all other orders. According to the expression of each order of the CGHs, their bandwidth can be presumed the same [33], and assuming that the main orders of emergent light are ± 1 order and zero order and the crosstalk of them are avoided, the tilted angle should meet the requirement that $\sin\theta/\lambda\le 1/(3a)$, where λ is the wavelength, a represents the pixel pitch of SLM. Both diffraction background noise of phase only CGH and that of SLM can be filter out by filtering architecture [19]. In order to obtain more high frequency information of the target wavefront and higher diffraction efficiency, the filtering aperture ought to be large enough. In a filtering system employing a Fourier transform lens with the focal length of f', the maximum filtering aperture can be acquired as

$$D_{\max}=\frac{\lambda f'}{3a}. \tag{3}$$

This filtering aperture also indicates the bandwidth limitation. It should be pointed out that the bandwidth and band limitation are the cases in the method of [19], which is not applicable to some other methods because they have their own band limitations [25].

2.2 Color display via complex amplitude modulation

There are several methods to realize color holographic display [28, 34-35], where time-division multiplexing method can effectively reduce the size of system. Therefore, time-division multiplexing combined with CAM is a conducive way to miniaturize the whole system. It is the reason that we apply time-division multiplexing method in our color display. The parameters in the practical optical system should be determined firstly for red, green and blue channel to acquire a best display effect. In the realization of CAM, the physical coordinates for each channel on back focal plane of Fourier transform lens are not the same. The frequency plane coordinate u is defined as $u = x/(\lambda f)$, which indicates that the frequency coordinate is wavelength dependence. Consequently, in the time-division multiplexing system with a filtering architecture, the effective order for each color channel locate at distinct positions on the same frequency plane, which means they cannot be filtered out from all orders of CGHs and the SLM. To simplify the system the unification of three effective orders' location is necessary. The maximum tilt angle for each channel follows $\sin\theta_{\max} = \lambda/(3a)$, which indicates that $\theta_{\max}$ is proportional to wavelength. Hence, the tilt angles should be set according to the minimum wavelengths in the system $\sin\theta = \lambda_{\min}/(3a)$ for the acquisition of a same effective order position. Then, the filter aperture position is $\lambda_{\min} f/(3a)$. Despite the fact that the reduction of the tilt angles for longer wavelength channels sacrifices little high frequency component of them, the main information is retained and reconstructs the final color scene.

2.3 Bandlimited initial phase in a complex amplitude modulation

Random phase distribution brings the character of diffusion for object surfaces, which causes the light reflected to more directions in free space. As a result, more information of objects from different angles can be recorded and reconstructed in holography, which will be helpful to display the target scene with a wide viewing angle. Mathematically, a total random phase has an infinity bandwidth; on the other hand, the spatial frequency domain is bandlimited in the CGH calculation. This conflict causes the calculation speckle noise [3]. Thus, in the applications of most complex amplitude modulation methods, a non-random initial phase can effectively gather the main information round the center of spectrum; however, the intensity for high spatial frequency information decrease, which suggests the information that is observed from larger angle. To balance the pros and cons of them, the bandlimited initial phase is introduced onto the object surface. An initial phase distribution is pre-generated by optimized CGH algorithm [5] to ensure the limited bandwidth. The bandlimited initial phase Φ_{band} (and the frequency information of $\exp(j\Phi_{band})$ is F_{Φ}) is imposed on the object surfaces Σ with an amplitude distribution of A_{Σ} (and its frequency information F_{Σ}), which can be descripted by $A_{\Sigma} \bullet \exp(\Phi_{band})$. According to the feature of Fourier transform, it can also be presented as $F_{\Sigma} \otimes F_{\Phi}$, where "$\otimes$" represents convolution operation. Both F_{Φ} and F_{Σ} are bandlimited, so the final target complex amplitude information in frequency domain is given by

$$\begin{aligned} F = F_{\Sigma} \otimes F_{\Phi} &= \iint_{-\infty}^{\infty} F_{\Sigma}(u,v) F_{\Phi}(u-\xi, v-\zeta)\, d\xi d\zeta \\ &= \int_{-\Delta_{\Sigma v}-\Delta_{\Phi v}}^{\Delta_{\Sigma v}+\Delta_{\Phi v}} \int_{-\Delta_{\Sigma u}-\Delta_{\Phi u}}^{\Delta_{\Sigma u}+\Delta_{\Phi u}} F_{\Sigma}(u,v) F_{\Phi}(u-\xi, v-\zeta)\, d\xi d\zeta, \end{aligned} \tag{4}$$

where $\Delta_{\Sigma u}, \Delta_{\Sigma v}$ and $\Delta_{\Phi u}, \Delta_{\Phi v}$ are the half bandwidth of F_{Σ} and F_{Φ} along u and v axis respectively. That indicates that F is also bandwidth limited. Compared this CAM method introduced in Section 2.1 and iterative algorithms, the proposed method can effectively enhance the target information. This can guarantee that theoretically the filtering operation will not cause information loss. Moreover, Eq. (4) indicates that the intensity of high frequency is higher than that in the method with non-random initial phase. This is the reason why the proposed method can widen the viewing angle for holographic displays based on traditional CAM methods. Furthermore, the time taken by the proposed method is similar with the approach in [19], because bandlimited initial is pre-calculated and there is no iteration process, which shows that the proposed method can also be applied to dynamic display. It is worth noted that a bandlimited initial phase cannot be a total random one, so here the “bandlimited random initial phase” is a pseudo random phase. The analysis in Sec. 2 is based on the system in [19], but it doesn't mean that the proposed method can only be used in a specific CAM method. According to mathematical discussion, the proposed method can also be used in other holographic displays based on CAM with filtering architecture by modifying corresponding parameters. In summary, the proposed method can provide a wider viewing angle and high performance holographic display.

3. Verifications

To verify the feasibility of the proposed approach, we firstly perform the numerical simulation. The bandlimited phase distribution is acquired by improved iteration method based on Fidoc algorithm, because the iteration algorithm is an easy way to obtain a target phase distribution that can reconstruct the given intensity pattern. The simulations are performed with Matlab on Intel Core i7-6700HQ 2.6GHz, 8GB RAM, where the wavelength is set as 632.8 nm, the resolution of images and CGHs are 512 × 512, the pixel sizes are 3.74 μm. One can learn from the results (Fig. 1) that the proposed method could achieve high quality reconstruction, for the peak signal-noise-ratios (PSNRs) [36] of the results are 28.3513 dB, 27.7372 dB, and 22.9786 dB. Moreover, the computation time of these three calculations are 0.06 s, 0.08 s, and 1.25 s. As shown, the calculation time approximates to CAM method in [19], because the band limited initial phase is pre-calculated and there is no more calculation process introduced. This means the proposed method is also appropriate to be employed in dynamic holographic display.

Fig. 1. The simulation results of 2D scenes, where (a) is the original image, (b), (c) and (d) are reconstructed by method in [19], proposed method, and iteration method (G-S algorithm with 5 loops) respectively.

Furthermore, 3D scenes are numerically reconstructed by CAM without and with bandlimited initial phase respectively, where the targets are a plate of apples and a chessboard background with the size of 5 × 5 × 3 mm and 8 × 8 mm respectively and they are 35 mm from each other. The resolution of CGH is 3840 × 2160, the wavelengths are 632.8 nm, 532 nm and 473 nm, and the pixel pitch is 3.74 μm. In the calculation, the object wavefront on holographic plane is acquired based on multi-layer angular spectrum method [30] meanwhile the hidden surfaces are removed [37]. The results are exhibited in Fig. 2. When one focus on the front object the rear one becomes blurred and vice versa, which verifies that the proposed method realize 3D display successfully.

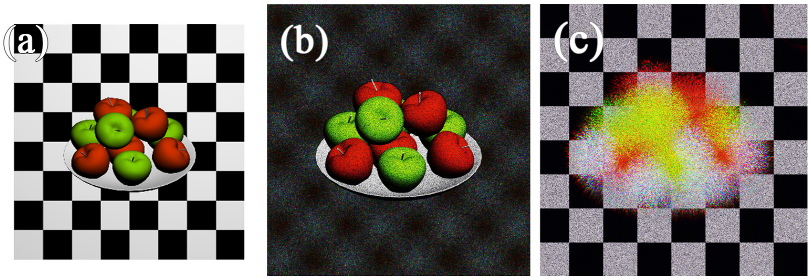

Fig. 2. The simulation results of reconstructed 3D scenes by proposed method, where (a) is the scheme of target scene, (b) is focused on the plate of apples while (c) is focused on the chessboard.

In the optical experiment, we employ a phase-only SLM (Jasper 4K phase-only SLM) with the resolution of 3840 × 2160 and the pixel pitch of 3.74 μm. The optical set up schematic is shown in Fig. 3. A time-division multiplexing system with a filtering architecture is employed to simplification. As shown in the figure, three laser sources with the same wavelengths in numerical simulations are collimated by the same collimation system. In the setup, the polarizers and half wave plates are employed to ensure the polarization directions of laser beams match that of SLM. Shutters are used to control three lasers beams illuminated on SLM sequentially, which are synchronized with SLM so that the target scene can be reconstructed in each color channel by corresponding CGHs. After the filtering architecture, the reconstructed scene is recorded by a digital camera (Canon EOS 550D with EF-S Lenses 18-85) at two positions to capture the images from different view angles. All parameters about the 3D scene are the same as these in numerical simulations.

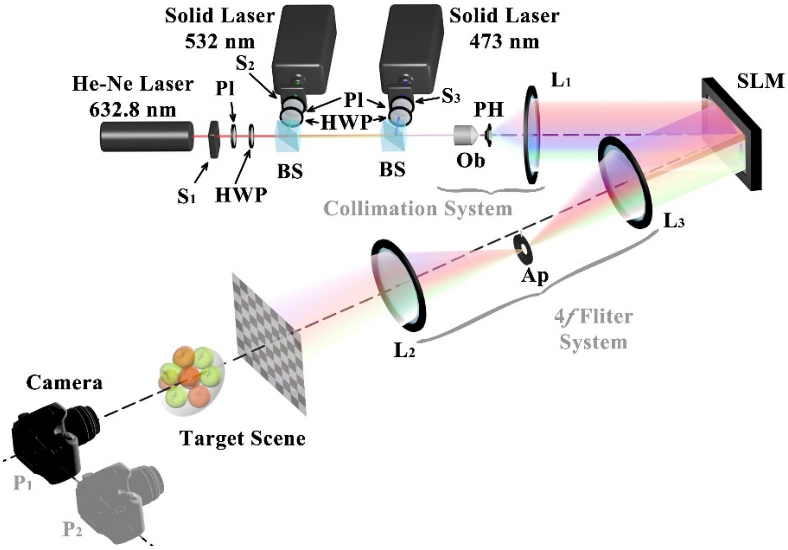

Fig. 3. The schematic of optical experiment. S_1, S_2 and S_3 are shutters, HWP represent half wave plates, Pl are polarizers, BS are beam splitters, Ob is the objective, PH means pin hole, L_1, L_2 and L_3 are lenses, and Ap is an aperture. Objective, pin hole and the collimating lens L_1 constitute collimation system to extend the laser beams and collimate it as plane waves. A 4*f* filter system consist of Fourier lenses L_2 and L_3 and the aperture for filtering out unwanted orders. A digital camera is applied in the experiment to record the target scene at the view positions P_1 and P_2.

The results captured in optical experiments are shown in Fig. 4. Figure 4(a)–4(c) are results by traditional CAM method in [19], while Fig. 4(e)–4 (g) are those by the proposed method. When the camera focuses on the front plane [Fig. 4(a) and Fig. 4(d)] the plates of apples are clear while the chessboards become blurred, and vice versa [as shown in Fig. 4(b) and Fig. 4(e)]. Hence, Fig. 4(d) and Fig. 4(e) proofed that the feasibility of 3D holographic display by the proposed method. For further study on the display effect by proposed method (for easier comparison, we consider the state that front objects are on focus), we captured the images at both zero viewing zone P_1 [Fig. 4(a) and Fig. 4(d)] and non-zero viewing zone P_2 that is 3 cm away from the axis horizontally [Fig. 4(c) and Fig. 4(f)]. When observing position goes to a farther one for a lager observation angle, information loss is conspicuous by the complex amplitude method with constant initial phase – the right part of target scene is almost missed, as shown in Fig. 4(c). However, the loss is restrained effectively by our proposed method [Fig. 4(f)]. It is easy learnt that the modulation with bandlimited random initial phase provides a larger viewing angle.

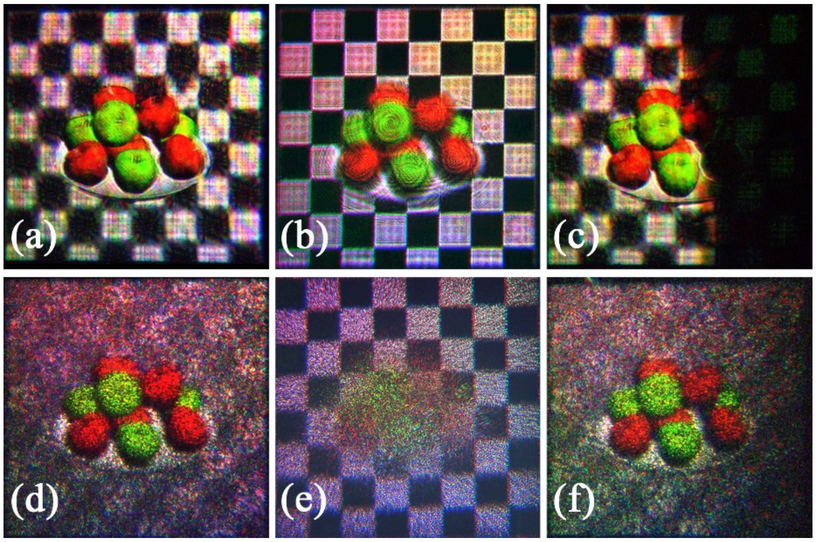

Fig. 4. The optical experimental results by the CAM without/with bandlimited random initial phase, where (a), (b), (d) and (e) are captured at P_1, while (c) and (f) are recorded at P_2. (a), (c), (d) and (f) are focused on the front object, while (b) and (e) are on the rear one.

Moreover, we also perform a dynamic display based on the proposed method. To achieve a better display effect, another phase-only SLM (Holoeye PLUTO-VIS) is applied to replace the SLM from Jasper in this dynamic display verification for it can achieve 60 Hz frame rate, whose pixel pitch is 8 μm. The result is recorded by a digital video, SONY HDR-XR160E. 2 frames are extracted from the recorded video and demonstrated in Fig. 5. The different sets and characters of the recording devices lead to the different depth of view and color balance in the results. Learnt from the result, the proposed method can be successfully used in color dynamic holographic displays.

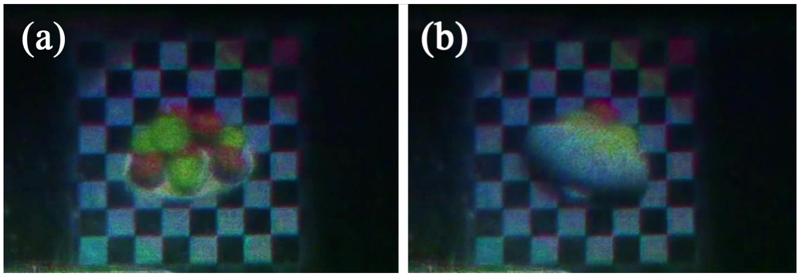

Fig. 5. Dynamic display by proposed method (Visualization 1), (a) and (b) are the extracted frames.

It is noted that the PSNR is lower than the simulation result by the method in [19] and there is more calculation speckle in 3D reconstruction. A series of reasons lead to this situation, such as inappropriate optical elements' positions and other parameters in the system. The most vital one is the initial phase is not strict bandlimited for the use of iteration algorithm. However, an optimized initial phase would bring a better result. Furtherly, it is shown in Fig. 4 that the reconstructed scene by the proposed method has a smaller viewing depth: when focused on front objects the rear ones are more blurred. This means that the proposed method is closer to realistic situation and it provides a better depth cue of accommodation. It should be pointed out that the viewing angle in the proposed method aims at widening the viewing angle in holographic display based on CAM; but the angle is also limited by the pixelated structure of SLM [38], which is not concerned about here. Moreover, in a certain holographic display system the spatial bandwidth product is also determined by the SLMs, which indicates that the total information that the system can display is finite. Theoretically, there is a trade-off relationship between two observation parameters, including viewing angle, size, image quality, and so on. One cannot achieve improving all of these display effects with keeping the same spatial bandwidth product, so a balance should be taken according to the practical requirements. In summary, compared with holographic display based on CAM without bandlimited initial phase, though there is little decay of image quality, a better viewing effect can be acquired by proposed method.

4. Conclusion

We realize color dynamic holographic display via CAM, and the viewing angle is widened by introducing bandlimited initial phase. Bandlimited initial random phase overcomes the drawback by constant initial phase on 2D or 3D scenes in traditional CAM, which directly decreases the viewing angle. The proposed method with pre-calculated bandlimited phase does not bring time-consuming process in the in-line calculation for CGHs, which provides the feasibility of realizing dynamic display. Theoretical discussion indicates the proposed method can effectively increase the viewing angle in holographic display based on CAM methods with smaller limited bandwidth, and both numerical simulation and optical experiment verify it. By applying a time-division multiplexing technique, a color dynamic display based on CAM successfully reconstructs the target scene while the whole size of system is not increase too much. Though a specific CAM based on optical holography is introduced and employed in the verification, the proposed method can also be utilized in other color dynamic holographic display system based on other CAM methods. To improve the image quality of experimental reconstructed scene by the proposed method, the further work is focusing on bandlimited initial random phase optimization. It is believed that the proposed method will be applied to holographic display by CAM to demonstrate a better display effect.

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