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Coherent backlight system for flat-panel holographic 3D display

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ABSTRACT

A coherent backlight system featuring a compact form factor is proposed for flat-panel holographic 3D display. The feasibility of the proposed system based on reflection hologram is experimentally verified by using a hologram to reshape the light scattered by a diffuser into a coherent output. The output of the backlight system is used for 3D image construction with a spatial light modulator, and 3D images with sharp edges and clear depth information are obtained.

1. Introduction

Holographic 3D display has attracted much attention recently, due to its potential to provide true 3D images [1–3]. Various holographic 3D display systems have been proposed, and most of these systems use spatial light modulator (SLM) based on digital micromirror device (DMD) [3]or liquid crystal (LC) [1,2] to modulate the incident light. Due to the requirement for coherence [4] and large size of the incident light during 3D image formation, lasers or light emitting diodes (LEDs) with complicated optical components are usually needed in these systems.

In current holographic 3D display systems, the backlight units usually employ lenses [3] and spatial filters [5] to expand the laser beam to a proper size and to improve the coherence of the LED light source. These optical components require sufficient space to function properly, and make the holographic 3D display system too bulky for practical applications. On the other hand, conventional backlight units used in flat-panel 2D displays consist of diffusers or other diffusive components that would degrade the coherence of the incident light, which is essential for holographic 3D display.

In this paper, a coherent backlight system based on reflection hologram is proposed for flat-panel holographic 3D display. In order to obtain a large scale coherent plane wave output while maintaining a compact form factor, a reflection hologram previously recorded is used in place of a conventional beam expander to convert the scattered laser input. In Section 2, the feasibility of using a scattered wave as a reference beam to reconstruct a plane wave object beam through a reflection hologram is discussed, and the proposed backlight system is described in details. A proof-of-concept experiment and the results are presented in Section 3, and discussion is given in Section 4.

2. Design of coherent backlight system

2.1. Light source

Light source is an important component in a backlight system. In holographic 3D display, coherence of the light source directly affects the holographic 3D reconstruction with SLM [5]. Both lasers and LEDs have been used as a light source in current holographic 3D display systems. However, when using LED for holographic reconstruction purpose, spatial filter is usually needed to improve the spatial coherence of the LED light source. Moreover the pinhole structure within the spatial filter greatly reduces the light intensity, resulting in a relatively low light efficiency of the backlight system. Therefore we consider laser as light source in our backlight system for better coherence and higher light efficiency.

2.2. Compact expander

Collimated laser beam should be expanded to a proper size to illuminate the whole active region of SLM, as every pixel in the active region contributes to the reconstructed image. Conventional beam expanders composed of a telescope configuration of two lenses along a common axis are capable of expanding the

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laser beam, but they need considerable optical length or space to function properly, and this makes them unfit for a flat panel purpose. Although there have already been compact expanders that use the optical folding method [6,7], folded optics can only shorten optical length in one dimension, and still need additional space for the folded optical path, which limits the aperture ratio of the whole device.

What we propose is a compact holographic expander, with a diffuser to scatter the incident light into a large area, a reflection hologram previously recorded is then used to reshape the scattered light field into a coherent one. This method is valid according to the theory of holography with extended source [8], and it had already been adopted in data storage security [9] and high capacity data storage [10]. Despite the fact that current applications are limited to amplitude information storage, this method is also capable of phase information preservation.

In holography, a hologram is created by recording the interference fringes of object beam O and reference beam R both derived from the same laser source [11]. The energy of the combined beams can be described as:

$$|O+R|^2 = |O|^2 + |R|^2 + OR^* + O^*R \tag{1}$$

where the amplitude and phase of the object and reference beams are represented by the modulus and argument of the complex numbers O and R, respectively. When these interference fringes $|O+R|^2$ are recorded on a holographic plate, the amplitude and phase of both object beam O and reference beam R are also recorded in the form of OR^* and O^*R, respectively. The transmittance T of the recorded holographic plate is proportional to the energy of the interference fringes, as expressed by Eq. (2):

$$T = k|O+R|^2 = k|O|^2 + k|R|^2 + kOR^* + kO^*R \tag{2}$$

where k is a constant denoting the linear recording of object and reference beams.

After exposure, either object or reference beam can be used to reconstruct the other [12]. When a reading beam U is incident on the recorded material, the complex light field H can be expressed as:

$$H = TU = k(|O|^2 + |R|^2)U + kOR^*U + kO^*RU \tag{3}$$

When the original reference beam R is used as the reading beam, the second term on the right side of Eq. (3) resembles the object beam O with the same phase and scaled amplitude in the form of $kO|R|^2$. When the original object beam O is used as the reading beam, the third term on the right side of Eq. (3) resembles the reference beam R with the same phase and scaled amplitude in the form of $k|O|^2R$.

As either beam can be used to reconstruct the other, we use a scattered wave and a plane wave both derived from the same source to form a reflection hologram, as shown in Fig. 1(a). During reconstruction, instead of the conventional use of plane wave as the reading beam, the scattered wave is used as the reading beam to reconstruct the plane wave, as shown in Fig. 1(b). This configuration benefits from the use of a hologram to ensure the coherence of the output, thus the coherence of the light during beam expanding procedure is no longer required, so that a diffuser can be utilized to spread the laser beam into a large area. As a result, the whole backlight system could be very compact. Moreover, in reflection hologram geometry, as shown in Fig. 1(b), only the reconstructed plane wave propagates backward as output, the undiffracted and conjugate beams propagate in the opposite direction until absorbed, leaving the output unaffected.

2.3. Schematic backlight system setup

We use laser as light source and holographic expander to achieve both compact structure and coherent output. In Fig. 2, the laser source is guided into a diffusive component, which by proper design could work in an edge-lit fashion and scatter the laser beam to illuminate the holographic layer uniformly [13]. The surface of the diffusive component should be specially processed, e.g. by using metallic coating, to prevent light leakage in undesired directions. Then the scattered light is incident on the

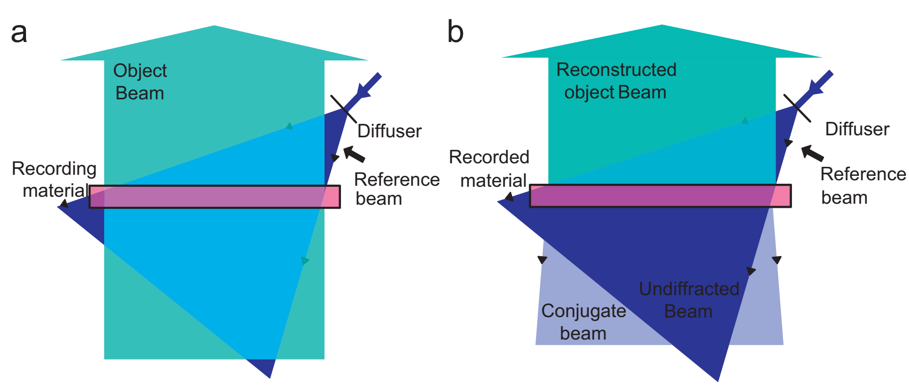

Fig. 1. Reflection hologram formation (a) and reconstruction (b) with scattered reference beam.

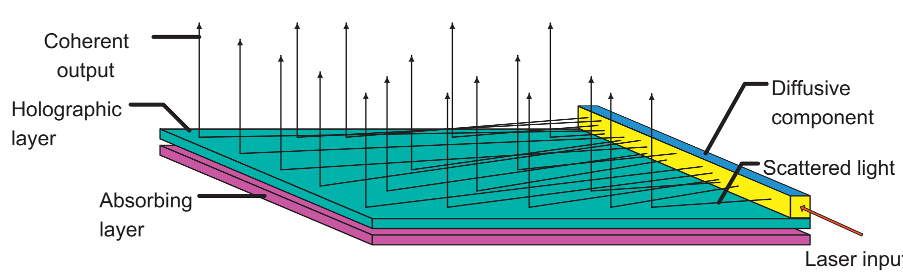

Fig. 2. Schematic system setup of the proposed coherent backlight system.

holographic layer uniformly, and it is diffracted into a plane wave, forming a coherent and uniform output. The undiffracted and conjugate waves propagate downward, until absorbed by an absorbing layer placed beneath the holographic layer.

The total output efficiency of the backlight system depends mainly on the diffraction efficiency of the hologram, and the diffusion efficiency of the diffusive component which is defined as the ratio of the light scattered from the diffusive component to the light guided into it. As for the hologram with extended source proposed in this paper, the diffraction efficiency could reach a maximum value of 64% theoretically [16], and the diffusive component that operates in an edge-lit fashion has been reported to diffuse 90% of the incident light [13].

3. Experiments and results

In order to prove the feasibility of the proposed coherent backlight system, the compact holographic expander is verified by a proof-of-concept experiment. A functional holographic expander is fabricated, and illuminated with scattered light to reconstruct a plane wave. The output is directed to an SLM to form a holographic 3D image with depth information, which proves that the output wave front could be used for holographic 3D display.

We use polymer dispersed liquid crystal (PDLC) as recording material for its high diffraction efficiency and no need for post-treatment. The PDLC mixture comprises 35.4 wt%:13 wt%:1 wt%: 0.6 wt%:51 wt% of TMPTA monomer (Aldrich): N-vinylpyrrollidone

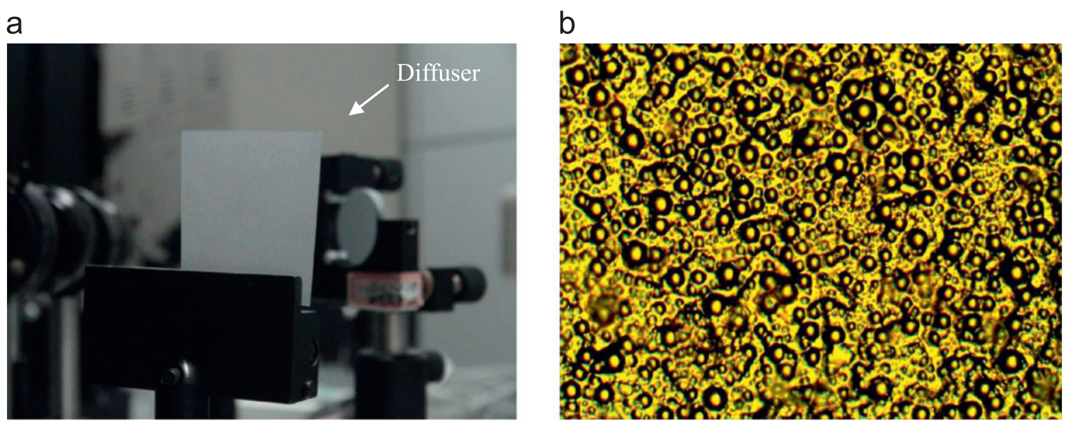

Fig. 3. (a) A diffuser from LCD backlight unit and (b) diffuser under microscope (100 ×) showing randomly structured surface.

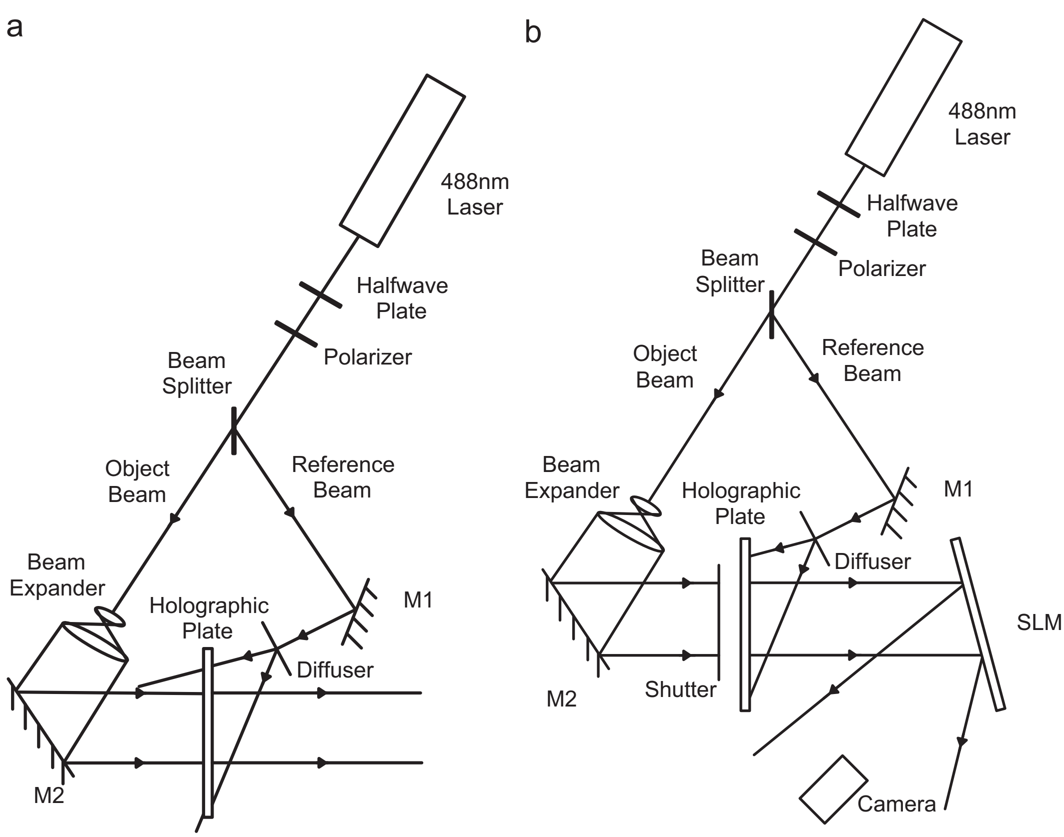

Fig. 4. Experimental setup for (a) hologram recording and (b) plane wave reconstruction.

(Aldrich): N-phenylglycine (Aldrich): Rose Bengal (Aldrich): LC (5CB, HCCH), and is made uniform by magnetic stirring in the dark. The holographic plate is a glass cell (2.5 cm square) with the thickness controlled by Mylar spacer (50 μm), and the PDLC mixture is filled by capillary action. The diffusive component used in our experiment is a fragment of diffuser from a conventional liquid crystal display (LCD) backlight module, as shown in Fig. 3. Although the diffuser used here is different from the one proposed in the schematic backlight system setup, they are both intended to scatter the incident light into a large area. However, for practical applications, the diffuser should be well designed as required in the schematic backlight system setup to ensure the homogeneity of the scattered light on the holographic layer.

In Fig. 4(a), light emitted from a 488 nm laser (COHERENT Co.) firstly passes through a half wave plate and a polarizer to ensure a horizontal polarization required by the SLM(PLUTO, Holoeye), then it is split by a beam splitter into two components: reference and object beams. The object beam is expanded to 1.5 cm in diameter by a beam expander and projected onto the holographic plate. The reference beam passes through the diffuser and is incident on the holographic plate from the other side. The light intensities of both reference and object beams are adjusted to 1.0 mW/cm^2, and the scattered reference beam is adjusted by changing the incident angle of the light reflected from M1, and the position of the diffuser to provide a nearly uniform illumination on the holographic plate. The exposure lasts 2 min.

As shown in Fig. 4(b), after the exposure, the object beam is blocked by a shutter, and the reconstructed plane wave occurs. This reconstructed beam is directed to the SLM with a computer generated hologram (CGH) loaded on it, a camera is used to detect the constructed 3D image. The holographic plate after the exposure is shown in Fig. 5. Under the optical microscope (100 ×), randomly distributed microstructures on the surface of the sample are observed, as we use scattered reference beam during the hologram recording.

The CGH loaded on the SLM is calculated using the Kinoform algorithm [14], as shown in Fig. 6(a). The 3D image constructed by the SLM consists of letters ‘A’ and ‘B’ located at different depths, and letters ‘A’ and ‘B’ are designed to be 2 m and 1 m away from the SLM, respectively.

In Fig. 7, we present some snapshots of the holographic 3D images formed by the SLM using original plane wave and reconstructed plane wave, respectively. The original plane wave is tuned by an attenuator to prevent saturation during image capture, and also to adjust the image brightness for a better 3D image quality comparison between the original plane wave and the reconstructed plane wave. As can be seen in Fig. 7(a) and (b), when the camera focuses on one letter, the edges of the letter become sharp, and the other letter becomes out of focus and blurred. The central bright area in the image results from the zero-order diffraction as we use a reflection type SLM in our experiment, and could be alleviated through proper calibration in the CGH algorithm [18].

In Fig. 7(c) and (d), there is no significant distortion in the image formed by the reconstructed plane wave, and the depth information is well preserved, which is demonstrated by focusing on letters ‘A’ and ‘B’ at different depths in space. The diffraction

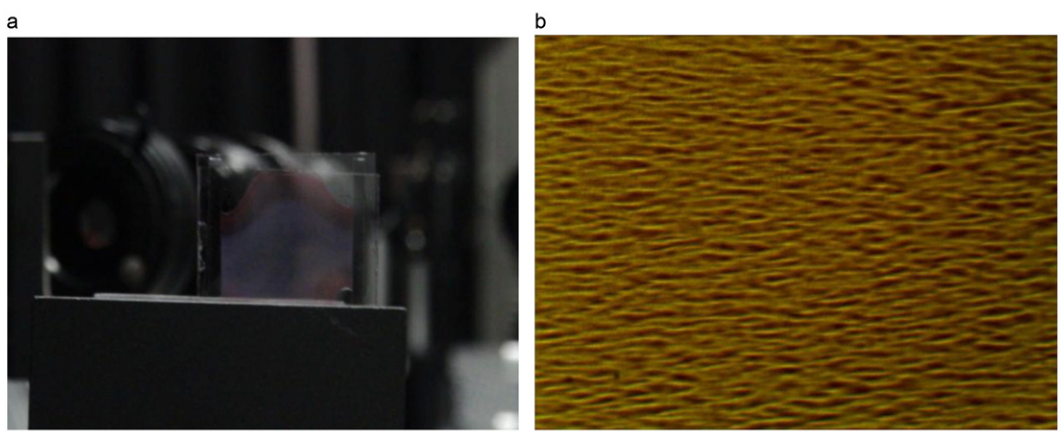

Fig. 5. (a) Holographic plate after the exposure, (b) under optical microscope (100 ×).

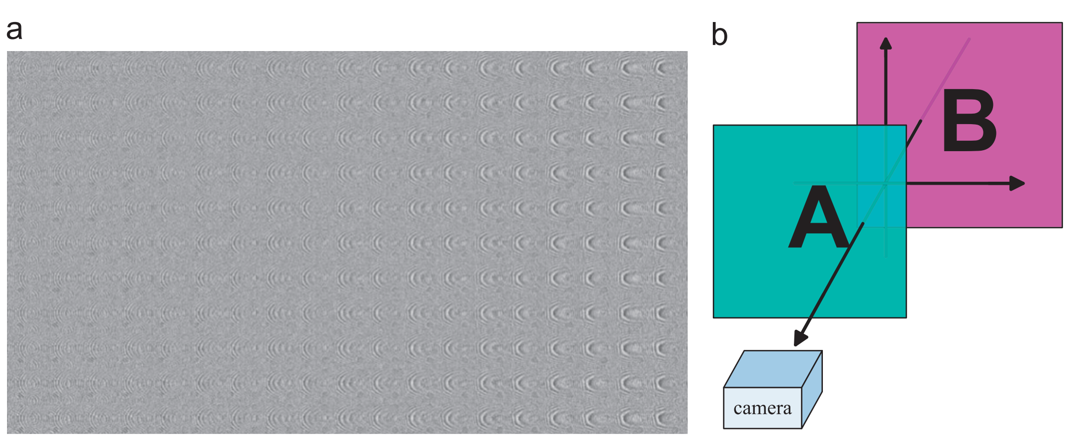

Fig. 6. (a) Computer generated hologram loaded on the SLM and (b) schematic diagram of the constructed 3D image in space with respect to the camera.

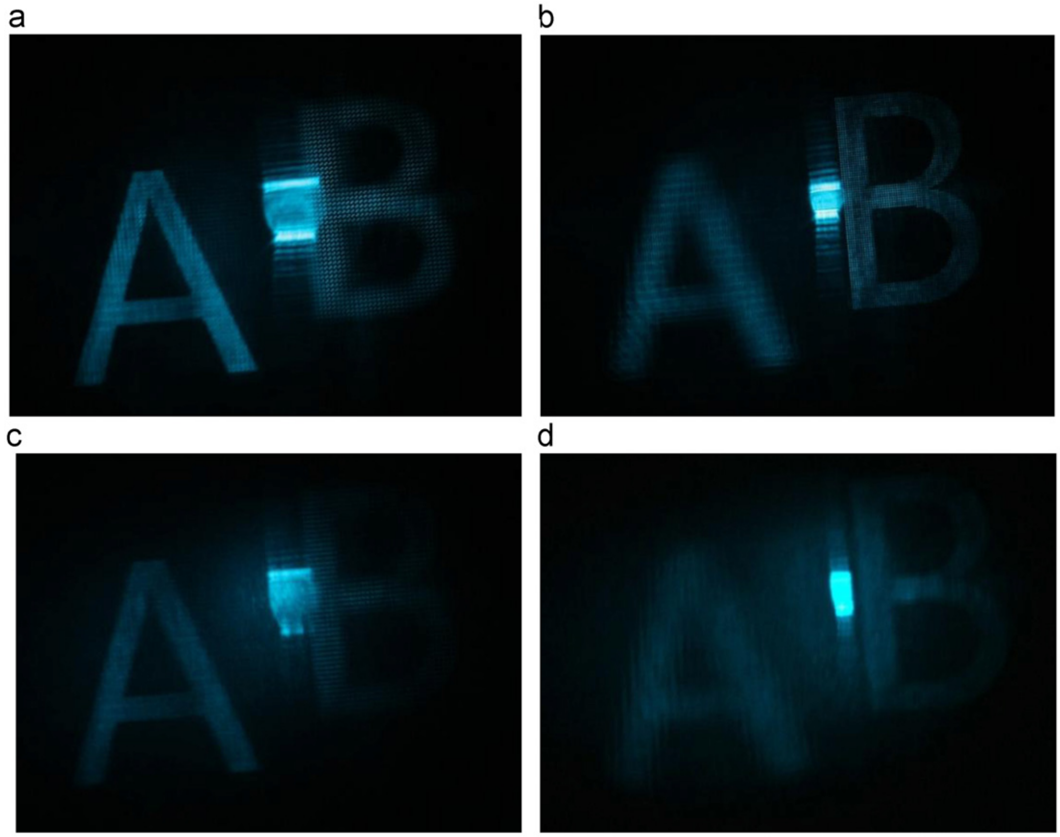

Fig. 7. Images captured by camera, with original plane wave and focusing on (a) letter 'A', (b) letter 'B'; with reconstructed plane wave and focusing on (c) letter 'A', and (d) letter 'B'.

efficiency is defined as the ratio of the intensity of the reconstructed plane wave to that of the scattered reference beam, and is measured to be 0.3% in our experiment, which accounts for the dimmer images in Fig. 7(c) and (d) compared with the bright images in Fig. 7(a) and (b). The limited diffraction efficiency mainly results from the fact that the holographic plate used has multiple layers with different refractive indices causing multiple reflections at the interfaces during the hologram recording. However, this problem could be solved by anti-reflection coating on the surface and index matching process between different layers, which would enhance the diffracted beam by two orders of magnitude [15].

4. Discussion

The proposed backlight system may benefit from the use of a holographic expander to achieve both compact system dimension and coherent output for holographic 3D display. However, the experiment is only a proof-of-concept one, many issues need to be addressed when a practical backlight system is fabricated. Firstly, the diffusive component should be well designed to provide a uniform illumination over the holographic plate. Secondly, the holographic layer should be firmly attached to the diffusive component to guarantee that the scattered field remains the same before and after hologram formation. Thirdly, the holographic plate should be covered by anti-reflection coatings and the index matching process must be included to obtain higher diffraction efficiency.

Furthermore, as a backlight system for display purpose, full color is always preferred. Although in our experiment we only demonstrated monochrome results, there is a possible solution to RGB full color by utilizing the electrically switching property of the PDLC materials [17]. One could use three layers of PDLC each corresponds to a specific color, by electrically switching on and off these layers, to achieve a field sequential color backlight system.

5. Conclusion

In conclusion, a backlight system for flat-panel holographic 3D display is proposed, which utilizes a diffusive component and a reflection hologram to obtain a compact form factor and a coherent output. The feasibility of the system is verified by a proof-of-concept experiment. Holographic 3D image construction with SLM using the backlight system is achieved. The proposed backlight system may be promising for the future holographic 3D display.

Acknowledgments

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