

Holographic printing for generating large-angle freeform holographic optical elements

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We propose a holographic printing technique for generating highly efficient large-deflection-angle freeform holographic optical elements (HOEs). For industrial device applications, the optical efficiency and deflection angle of HOEs are critical. To fabricate a high-frequency volume grating in a hogel, we design an optomechanical hogel recording system with a high angle deflection capability, which contrasts with the conventional printing scheme, the wavefront holographic printing technique featuring a paraxial deflection angle. With the proposed system, a large-deflection-angle HOE is experimentally demonstrated, and short-throw holographic caustic projection patterns are realized. © 2022 Optica Publishing Group

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Computational caustic projection has attracted lots of attention recently [1]. Smooth, freeform refractive surfaces generate a variety of caustic fields, including three-dimensional caustic-projection fields in space and two-dimensional images on curved surfaces. In practice, caustic freeform-surface lenses are thick and require expensive high-precision fabrication, as shown in Fig. 1(a). The design of freeform surfaces is categorized as an inverse problem and presents some computational challenges. Conventionally, a caustic-projection system has a smooth optical surface that refracts light to form an envelope of light rays, as shown in Fig. 1(a) [2,3]. As presented in Ref. [4], caustic-projection holographic optical elements (HOEs) with a freeform optical function produce a caustic optical field within a thin and flat HOE film, where the HOE replicates the optical function of arbitrary caustic-projection freeform surfaces holographically, as shown in Fig. 1(b). The caustic-projection HOE is different from a holographic stereogram that records the image of the spatial light modulator (SLM) on a hogel to give three-dimensional disparity. It has a relatively smooth phase profile as it follows the caustic freeform surface.

Although the mentioned method produces the caustic field successfully, further investigation of the spatial bandwidth raises

an interesting point in terms of deflection angle. In this Letter, we pose the design problem of large-angle freeform HOE projection, as depicted in Fig. 1(c). Recently, large off-axis and small form factor short-throw projection is increasingly needed in variety of applications such as augmented reality (AR) displays with small form factors [5–8]. Conventional freeform devices and systems are hard to design because their local surface gradients become too steep for high deflection angles, and a smooth freeform surface satisfying the design objective of short-throw projection cannot be found. Off-axis long-throw projection is also of interest because it can be obtained with a high-spatial-frequency volume hologram. In conventional wave-field holographic printing using SLMs [4], a long-throw caustic projection with paraxial deflection capability, as depicted in Fig. 1(b), is allowable. In Ref. [4], a maximum deflection angle of 10° was reported. Increasing the numerical aperture (NA) or deflection angle is hard because extending the NA of the HOE requires non-paraxial wave-field control.

In this Letter, we propose a digital HOE printing method that simplifies both the design and fabrication of short-throw caustic projection. Figure 1(d) compares types of caustic-projection HOEs in k-space. The long-throw caustic-projection HOE with a low-frequency bandwidth is constrained by the blue-colored circular spatial-band frequency range, while the short-throw caustic-projection HOE with high-frequency bandwidth is associated with a wider spatial frequency range. The upper bound of the spatial bandwidth is a parameter of the available holographic medium. From the point of view of the recording method, low-frequency and high-frequency or long-range and short-range HOEs can be realized through completely different approaches.

In Fig. 2(a), the conventional HOE recording method with bidirectional SLMs [4] produces long-throw caustic projection HOEs because the deflection power of the hogel is limited by the spatial frequency bandwidth and optical power of the wave field generated by the SLM. In Fig. 2(b), the reconstructed field is illustrated according to the reflection type of the HOE recording setup. The SLM-based wave-field recording scheme is advantageous since that complex field profile can be recorded on the hogel. However, the complex field control is limited only by

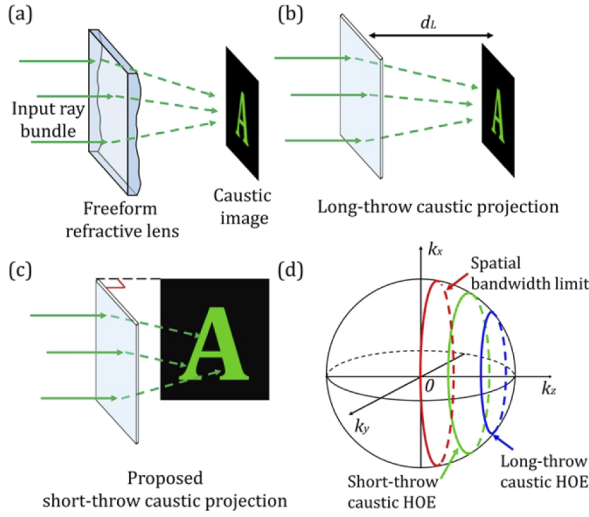


Fig. 1. Caustic projection schemes. (a) Freeform refractive lens, (b) long-throw HOE projection, and (c) proposed short-throw HOE projection. (d) Comparison of the bandwidths of the elements in k-space.

the NA of the objective lens. Non-paraxial control of the SLM wave field requires a more sophisticated optimization process and optical system.

We propose a practical printing method that uses an optomechanical direct-recording method, as depicted in Fig. 2(c). The key idea is that a printer head in a signal arm is rotated mechanically depending on the wavenumber vector of a ray sampled on a local region of the smooth freeform surface without using an SLM to modulate the signal wave, thereby avoiding the loss of optical power through the SLM. In our direct hogel recording method, the deflection angle from a single hogel is sufficiently enlarged by the wide angular range formed by tilting the printer head, leading to the fabrication of off-axis caustic-projection HOEs. The deflection angle is precisely controlled by two-axis goniometers, and a collimated laser beam is incident on a hogel in a designed direction, as indicated in Fig. 2(d). The single hogel is a volume hologram element, and its optical permittivity profile is represented by

$$\varepsilon_{m,n}(\mathbf{r}) = \varepsilon_s \text{rect} \left(\frac{x - mp_x}{p_x}, \frac{y - np_y}{p_y}, \frac{z}{t_0} \right) + \Delta\varepsilon V \left(\frac{x - mp_x}{p_x}, \frac{y - np_y}{p_y}, z \right) \cos(\mathbf{G}_{m,n} \cdot \mathbf{r} + \phi_{m,n}), \quad (1)$$

where ε_s and $\Delta\varepsilon$ are the substrate permittivity and the grating modulation strength, respectively, and (m, n) is the hogel index. t_0 is the hologram substrate thickness and p_x and p_y denote the x - and y -directional hogel intervals. $\mathbf{G}_{m,n}$ and $\phi_{m,n}$ are the volume grating vector and the phase shift of the (m, n) th hogel, respectively.

For a fixed reference beam vector $\mathbf{R}$, the signal beam vector $\mathbf{S}$ of the (m, n) th hogel is generated by $\mathbf{S} = \mathbf{G}_{m,n} + \mathbf{R}$ under the Bragg phase-matching condition. $\text{rect}(x, y, z)$ and $V(x, y, z)$ are the three-dimensional rectangular function and volumetric shape function of a hogel indicating the region scribed by the grating pattern. The entire HOE is represented by

$$\varepsilon(x, y, z) = \sum_{m=1}^M \sum_{n=1}^N \varepsilon_{m,n}(x, y, z), \quad (2)$$

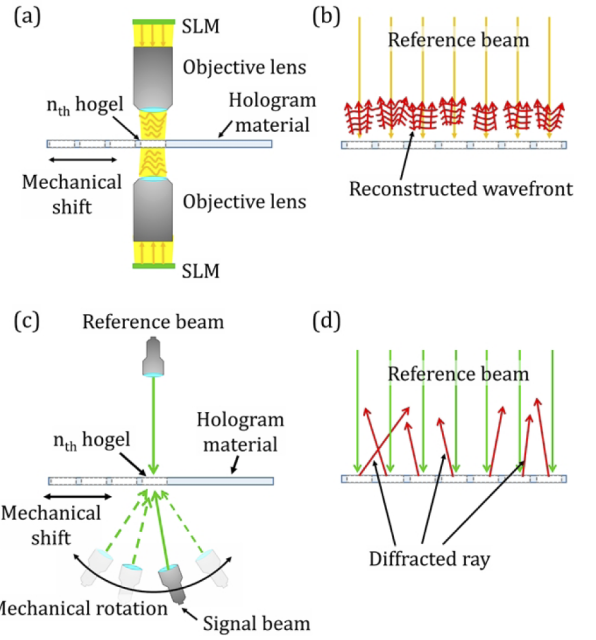


Fig. 2. Schemes for recording and replaying a caustic projection. The conventional scheme for (a) recording a HOE and (b) reconstruction. The proposed scheme for (c) recording a HOE and (d) reconstruction using mechanical signal beam steering.

where adjacent hogels can share an overlapping space around their border regions [9] but the hogels work independently in terms of ray-deflection performance due to the volume grating characteristics [10,11]. M and N are the numbers of hogels in the x and y directions, respectively.

We develop a prototype of the proposed high-spatial-bandwidth hogel recording system. The schematic design and photos of the implemented prototype are presented in Fig. 3. The system uses fiber optics to feed an optical wave into moving optomechanics. The pigtail-fiber-coupled 532 nm laser source (a Cobolt 04 series laser with a maximum power of 100 mW) is connected to a U-bench fiber-to-fiber coupler featuring a short free-space section in which a mechanical shutter blocks the optical field when the system changes the recording position hogel by hogel. After passing the U-bench, the optical wave is split into reference and signal waves by a 1×2 fiber coupler (PN530R5A1, Thorlabs; 50:50 split). The reference and signal fibers are guided by the cable carriers to reflective collimators (RC02AFC-P01, Thorlabs), where they form a Gaussian beam with a full width at half maximum of 1 mm.

The reference wave is collimated by the reflective collimator and illuminates the target hogel area of the HOE substrate in the normal direction. The signal wave is delivered to the other reflective collimator installed on the two-axis goniometer (a combination of a BGS80CC and a BGS50CC from Newport with rotation ranges of $\pm 30^\circ$ and $\pm 45^\circ$ in the x and y directions). The goniometer tilts this collimator so that the signal beam has a specific direction, as shown in Fig. 2(c). In the signal arm, a high-precision x - y stage (LTS-300/M, Thorlabs, with a traveling distance of 300 mm) moves the position of the goniometer such that the signal wave illuminates the target hogel area precisely. The origin of rotation of the goniometer is aligned to be on the HOE substrate, as seen in Fig. 3(a). A goniometer with a large tilting angle was chosen (rather than general tilting stages) so

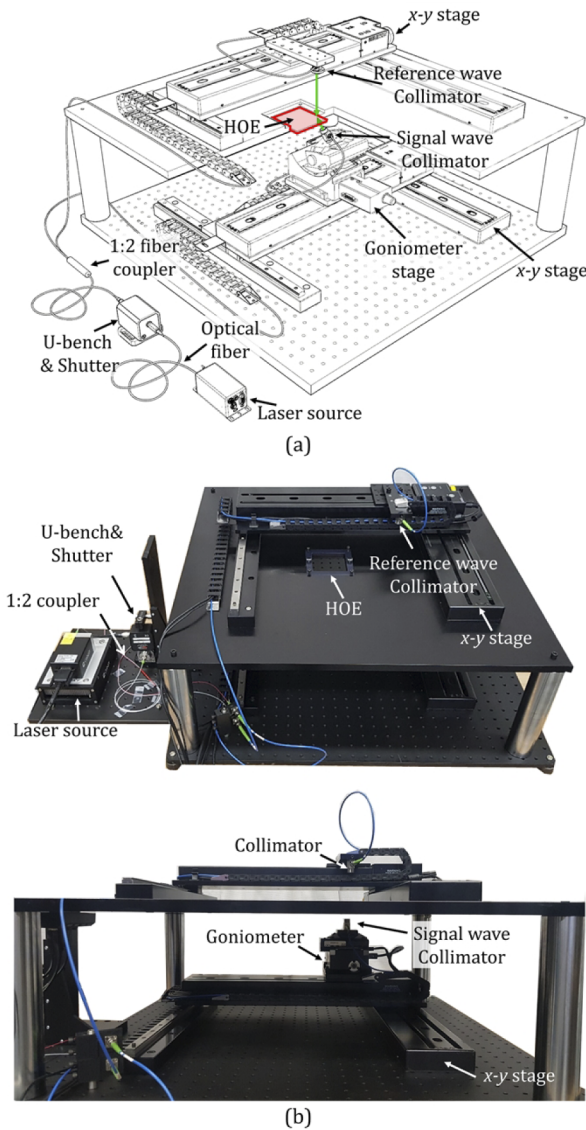


Fig. 3. Proposed system for recording caustic HOEs. (a) Schematic design and (b) implemented prototype.

as to be able to rotate the fiber-coupled collimator as widely as possible. Additionally, the reference arm on the two-axis linear stage operates such that the reference wave is synchronized to the signal wave and these interfere with each other at the same position on the HOE substrate.

In our system, the signal arm and reference arm are scannable over the $75 \times 75 \text{ mm}^2$ area of the HOE, since the HOE substrate (a photopolymer, Bayfor HX200, Covestro) has a permittivity $\epsilon_s = 2.25$ and a grating modulation strength $\Delta\epsilon = 0.015$. The system does not use a hard stop aperture to define a recording domain, and the signal arm and reference arm are moved at 1 mm intervals. The resulting hogels are 1 mm apart, and the removal of the hard stop aperture causes them to slightly overlap each other over the tail of the Gaussian distribution defined by $V(x, y, z)$ in Eq. (1).

Figure 4 presents an example of an off-axis long-throw caustic HOE printed by the proposed system (see Visualization 1). The target image plane is tilted from the direction of the reference wave by about 30° in order to separate the caustic image from

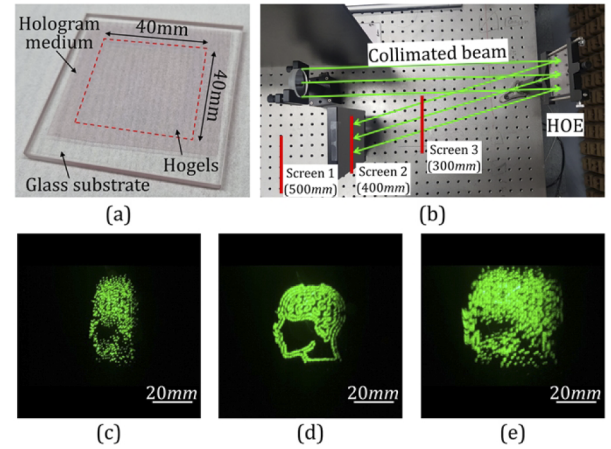


Fig. 4. Experimental results for an off-axis long-throw caustic HOE projection. (a) Printed HOE of size $40 \times 40 \text{ mm}^2$ and (b) the reconstruction setup. Projected caustic images are observed at three depth planes from the HOE: (c) 500 mm, (d) 400 mm, and (e) 300 mm (hogel diameter: 1 mm, hogel recording pitch: 1 mm, resolution: 40×40 ; see Visualization 1).

the DC beam. The hogel size is 1 mm and the total HOE size is $40 \times 40 \text{ mm}^2$, meaning that the hogel resolution of the recorded HOE is 40×40 hogels. In the reconstruction experiment, under normally incident illumination by the reference beam, the HOE generates 1,600 modulated ray bundles that are deflected to form the designed caustic-projection image. As described in Ref. [1], the caustic-projection design is formulated as an optimal transport problem of finding the mapping $\pi(\Omega)$ from the HOE plane to the image plane, where Ω is $(x, y) \in \mathbb{R}^2$. The target intensity distribution at the image plane can be interpreted using the probability measure $\mu_T(\Omega)$. The optimal design problem is defined as finding the optimal transport mapping $\mathbf{k}$ to minimize the objective function $|\mu_T(\Omega) - \mu_0(\Omega)|_{L2}$, which is the difference between the generated probability distribution $\mu_T(\Omega)$ and the target probability distribution $\mu_0(\Omega)$. The mapping $\pi(\Omega)$ is described by the ray-refraction vector $\mathbf{k}_{m,n} = (k_{x,m,n}, k_{y,m,n})$ at the (m, n) th hogel. The HOE is characterized by the $\mathbf{k}$ -vector set $\mathbf{k} = \{\mathbf{k}_{m,n}; 1 \leq m \leq M, 1 \leq n \leq N\}$ and generates the crossing-point distributions in the image plane. For a given HOE $\mathbf{k}$ -vector set, the crossing-point distributions in the target plane are interpreted via the probability distributions of $\mu_S(\Omega)$ and $\mu_T(\Omega)$ using a 2D Delaunay tessellation field estimator (DTFE) [12]. We employed a genetic algorithm to optimize the design [13]. In the design, the maximum deflection angle of a ray is set to 30° .

Figure 5 presents a short-throw caustic HOE that generates an off-axis caustic-projection image at the right-angle screen. We recorded 114×114 hogels with a pitch of 0.35 mm to represent a target image. The HOE recording in this experiment was performed with a pitch of 0.35 mm, which meant that hogel-to-hogel overlapping secured a resolution of 114×114 in the $40 \times 40 \text{ mm}^2$ HOE. A collimated laser beam illuminated the HOE at normal incidence. The hogels of the HOE reflected 9,725 rays toward the 90° -inclined screen to form the target illumination pattern. Experimental observations showed that the caustic image was successfully formed at the 90° -inclined screen. It is apparent that the large-angle deflection by the HOE works well and as intended by the design (see Visualization 2). A

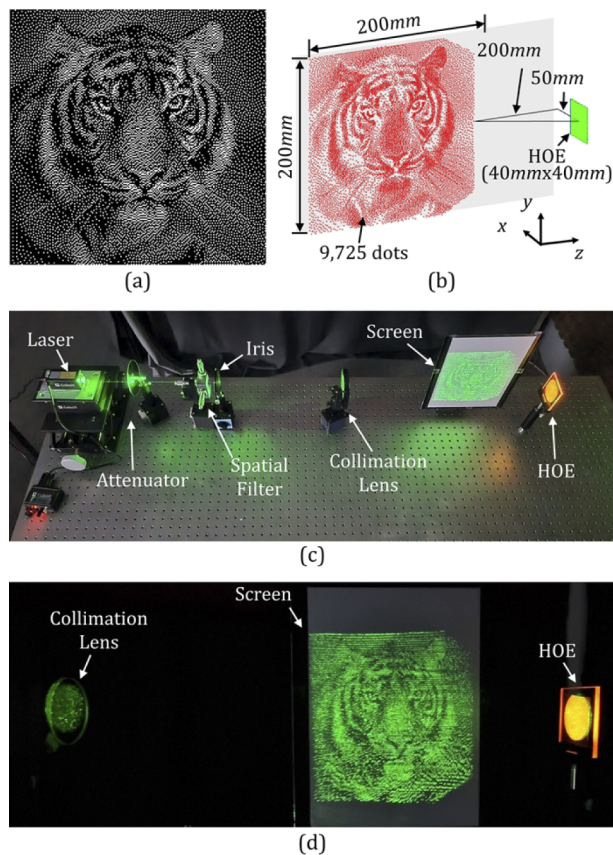


Fig. 5. Experimental results for a short-throw HOE projection. (a) Target image, (b) design schematic, (b) experimental setup, and (d) projected caustic image consisting of 9,725 rays at a right-angle screen 200 mm distant from the HOE (hogel diameter: 1 mm, hogel recording pitch: 0.35 mm, resolution: 114×114, size: 40×40 mm²; see Visualization 2).

projection lens with a throw ratio of less than 0.6 is usually called an ultra-short throw [14]. In this experiment, the throw ratio was 0.56, even without the lens. It should be noted that the pattern is not a diffractive inference pattern but a ray bundle distribution. The ray can be considered to be independently controllable interconnections from the hogel to its corresponding position on the screen. Since the pitch of the hogel is 0.35 mm and the width of the hogel is 1 mm, each hogel is overlapped by an adjacent hogel. Although the hogels are superimposed, each hogel deflects the beam at the recorded angle because volume holograms are capable of angular multiplexing [9].

In conclusion, we have proposed a holographic printing technique for a freeform HOE that has a threefold larger deflection angle (30°) compared to the deflection angle of a conventional caustic HOE (10°) and can successfully generate off-axis caustic projections. Our system records one sine wave on each hogel, so piecewise linear phase information is recorded instead of the ideal smooth curvature. To compensate for these shortcomings, we plan to upgrade the system so that the curvature of the phase information inside the hogel can be changed by controlling the divergence of the object light. It is believed that the proposed HOE could be a key device in various applications, such as optical interconnection, holographic displays, and AR displays.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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