Augmented Reality (AR) glasses are expected to redefine how we interact with real and virtual environments by overlaying rendered images within our visual Field Of View (FoV). To achieve this vision, recent years have seen a strong push from the scientific community to build AR glasses with high resolutions, wide FoV, and optical focus cues. However, the previous implementation of AR glasses, Beaming Displays [39], provides a limited resolution with 7 Cycles Per Degree (cpd) and 50 mm thick bulky AR glasses. Thus, the promises of Beaming Displays have yet to be fully realized.

An emerging design alternative to conventional designs for AR glasses, Beaming Displays [39] argues that designs should separate active and passive parts in AR glasses into discrete components. Specifically, these Beaming Displays project images from a distance (1-2 m) to a user wearing a passive lightweight optical eyepiece. Thanks to removing active components from AR glasses, Beaming Displays fundamentally avoid heating, computation, and power budget-related issues. At the core, Beaming Displays aim to balance design requirements such as form-factor, resolution, FoV, and optical focus cues. However, the previous implementation of Beaming Displays [39] provided a limited resolution with 7 Cycles Per Degree (cpd) and 50 mm thick bulky AR glasses. Thus, the promises of Beaming Displays have yet to be fully realized.

This paper introduces a new Beaming Display named HoloBeam following recent Computer-Generated Holography (CGH) algorithmic methods and holographic eyepiece designs. In HoloBeam, a holographic projector reconstructs multiplanar images at a target location away from that projector (1-2 m). As the reconstructed images are small, a user wearing an eyepiece made from a Holographic Optical Element (HOE) perceives a magnified version of the reconstructed multiplanar images. Unlike previous implementations of Beaming Displays, HoloBeam delivers slim AR glasses with high resolutions (24 cpd) and wide FoV (70 degrees). However, this exploration in improving Beaming Displays with HoloBeam comes at the cost of users being fixated in front of the projector, where
We also suggest our readers review Tbl. 1 as they read through this section. We believe our work could positively impact AR spirations in fixing issues related to weight, form factor, power, and computation. Beyond our review, we refer our readers to a survey by Chang et al. [21] on holographic AR glasses. To our knowledge, there are also variants of conventional AR glasses that can provide near-accurate optical focus cues [52]. Such VR headsets or AR glasses with optical focus cues are broadly categorized as varifocal [6, 31, 48], multiplane [25, 28, 57, 62, 78], focal surface [4, 33, 61], focus-invariant [51] and lightfield [4, 36, 55, 60, 74, 83]. Although all these types offer exciting solutions, to our knowledge, they largely suffer from problems related to weight, bulk, power, resolution, form factor, or heat.

Holographic AR Glasses. Unlike traditional focus supporting AR glasses, holographic AR glasses can manipulate both phase and amplitude of light, promising potential improvements in light efficiency, resolution, and dynamic range. Holographic AR glasses can offer sunglasses-like form factors HOEs [59] due to the use of thin diffractive optics. These holographic AR glasses can also offer high resolutions and support optical focus cues with continuous depth representations [59]. However, the eye-box of holographic AR glasses is typically limited due to the limited bandwidths of existing SLMs (étendue). To improve the eye-box of holographic AR displays, researchers explored opportunities in scanning a light source over an SLM or using multiple light sources [32, 41]. Unfortunately, these solutions arrive at the cost of hardware complexity and additional bulk.

Most recently, people have explored structured diffusers [54] and learned phase masks [13] to replace HOEs and expand the eye-box. But, these solutions typically arrive with image quality-related issues and require precision alignment in manufacturing. HoloBeam follows common holographic AR glasses that uses HOEs and shares similar shortcomings, namely eye-box-related issues. Unlike previous holographic AR glasses, HoloBeam offers significant improvements in fixing issues related to weight, form factor, power, and computation. Beyond our review, we refer our readers to a survey by Chang et al. [21] on holographic AR glasses. To our knowledge,

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**Table 1: Comparison between AR and VR near-eye displays.** Here, focus refers to the method used to support the optical focus cues. Optical see-through refers to the level of see-through in the real world. Wide eye-box refers to supporting varying gazes of users (above 10 mm). Moderate monocular fields of view are 20-50 degrees. Moderate resolution matches 10-20 cycles per degree. Although our work offers no mobility, it distinguishes itself as the slim and lightweight AR near-eye display, free from heating issues or limited power and computing resources.

<table>
<thead>
<tr>
<th>Focus</th>
<th>See-through</th>
<th>Eyepiece</th>
<th>Field of View</th>
<th>Resolution</th>
<th>Form factor</th>
<th>Weight</th>
<th>Power and Compute</th>
<th>Heat</th>
<th>Mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>CGH</td>
<td>Clear</td>
<td>Small</td>
<td>High Paper-Thin</td>
<td>Light</td>
<td>Expandable</td>
<td>No issue</td>
<td>Fixed</td>
<td>Limited</td>
</tr>
<tr>
<td>Beaming Displays [59]</td>
<td>Fixed</td>
<td>Moderate</td>
<td>Wide</td>
<td>Low Bulky</td>
<td>Regular</td>
<td>Expandable</td>
<td>No issue</td>
<td>Mobile</td>
<td>Limited</td>
</tr>
<tr>
<td>Holographic VR [57]</td>
<td>CGH</td>
<td>Blocks</td>
<td>Small Wide</td>
<td>High Thin</td>
<td>Regular</td>
<td>Limited</td>
<td>Issue Mobile</td>
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<tr>
<td>Video MR [53]</td>
<td>Multipane</td>
<td>Video</td>
<td>Wide Moderator</td>
<td>Moderate Bulky</td>
<td>Regular</td>
<td>Limited</td>
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<tr>
<td>Foveated AR [1]</td>
<td>Varifocal</td>
<td>Clear</td>
<td>Moderate Wide</td>
<td>High Bulky</td>
<td>Regular</td>
<td>Limited</td>
<td>Issue Mobile</td>
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<tr>
<td>Scanning Eyepiece [41]</td>
<td>CGH</td>
<td>Clear</td>
<td>Moderate Wide</td>
<td>Moderate Bulky</td>
<td>Regular</td>
<td>Limited</td>
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<td>Holographic AR [59]</td>
<td>CGH</td>
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<td>Lighthielf VR [56]</td>
<td>Lighthielf</td>
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<td>Pinlight Displays [60]</td>
<td>Lighthielf</td>
<td>Moderate</td>
<td>Small Moderate</td>
<td>Low Thin</td>
<td>Regular</td>
<td>Limited</td>
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<td>Microlens VR [55]</td>
<td>Microlens</td>
<td>Blocks</td>
<td>Small Narrow</td>
<td>Low Bulky</td>
<td>Regular</td>
<td>Limited</td>
<td>Issue Mobile</td>
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<td>Limited</td>
</tr>
</tbody>
</table>
We also provide the layout of HoloBeam in Fig. 1. The images generated using these SLMs could be imaged to the desired location using a set of lenses, forming 4f or 2f imaging systems or a more advanced multi-lens system. The conventional theoretical limits of Beaming Displays are covered in the original paper of Beaming Displays [19]. However, it should be noted that the limits of resolution in holographic approaches are an open scientific debate [53], which we also agree.

### 2.3 Computer-Generated Holography

CGH comprises a family of methods that approach the hologram calculation problem with algorithmic strategies [15][80]. Our readers could find an extensive survey of modern CGH methods in the work by Pi et al. [66]. The scene representation methods used at each CGH algorithm could help the categorization of CGH algorithms. Broadly, CGH can rely on scene representations based on the light field [40][41][71], multipane [42][76], and point clouds [22][59]. Alternative scene representations such as polygon based ones [38] are also available in the literature. There are also some algorithms which can help improve speed, accuracy, and image quality in CGH [20][23][54]. In our work, we follow multipane scene representations, and use gradient-based optimization methods used in many earlier works to generate a dataset of holograms [54]. Using this dataset, we derive a new learned-CGH pipeline. Unlike previous learned-CGH methods, our CGH optimization pipeline does not require depth information of a scene in hologram calculation and decides on the targets by itself. Our CGH pipeline runs at interactive rates on an average compute resource.

### 3 HoloBeam: Holographic Beaming Displays

HoloBeam requires three primary components for a complete display system. These components are a holographic projector, an eyepiece, and a software pipeline to help calculate 3D multipane holograms. We also provide the layout of HoloBeam in Fig. 1.

#### 3.1 Holographic Projector

Like other display systems, HoloBeam requires a light engine that contains light sources and an SLM. Given that HoloBeam is a holographic projector, it requires a coherent or partially coherent light source. In the meantime, the SLM of HoloBeam, could either modulate phase or amplitude of light or both - full complex. As depicted in the basic layout Fig. 1, the images generated using these SLMs could be imaged to the desired location using a set of lenses, forming 4f or 2f imaging systems or a more advanced multi-lens system. The conventional theoretical limits of Beaming Displays are covered in the original paper of Beaming Displays [19]. However, it should be noted that the limits of resolution in holographic approaches are an open scientific debate [53], which we also agree.

#### 3.2 Eyepiece

Our holographic projector modulates light to reproduce the desired light field near the user’s viewpoint. Since this light field is so close to the eye, the eye cannot focus on it. Besides standard optical components (e.g., lenses or mirrors), we can use HOE to convert this light field to images on the retina that users can accommodate and view.

Transmission HOEs. We base our work on transmissive HOEs using photopolymer films as the material (see Xiong et al. [79] for more). When the photopolymer film is exposed to light, the monomers polymerize according to the interference fringes, creating an unevenly distributed polymer structure. Because of the difference in refractive index between the monomer and polymer, this structure behaves as a phase hologram. If the thickness of the film is sufficiently thinner than the wavelength of the light, we can treat it as a volume hologram. Each diffraction grating structure formed within a volume hologram reflects a portion of the incident light. If the angle of incidence, if the optical path difference satisfies an integer multiple of the wavelength, all reflected light is intensified. In this case, the incident light is reflected almost entirely at one specific angle. This angle is called the Bragg angle, and the case where the incident light satisfies the Bragg angle is called the Bragg condition.

Based on this principle, diffractive optical elements using volume holograms are selective in wavelength and angle of incidence. Often the case, practically, it is sufficient to consider only the first-order reflected light in the numerical analysis of the reflection direction. If the incident light is sufficiently close to the Bragg angle and the wavelength at the hologram exposure, we can approximate its behavior well with Kogelnik’s coupled wave theory [67]. In this theory, the k-vector closure method (KVCM) gives the ray behavior of the incident light (Fig. 4).

#### Bragg Diffraction Analysis

From here, we briefly explain the theory of Bragg diffraction [29][49][50][67]. Fig. 3b describes the behavior of incident light in a transmission volume hologram. In this explanation, we also assume the wave vectors are defined inside the photopolymer medium. In real use cases, we have to consider the refraction and reflection at the boundary between the air and the photopolymer plate that consists of several layers, including a protection layer.

Let \( \mathbf{n}_c \) be the wave vector of the reference beam incident on the photopolymer plate when creating a volume hologram, and \( \mathbf{n}_i \),
be the wave vector of the signal beam incident from the opposite side of $\mathbf{n}_r$. Then, assuming that the two vectors have the same wavelength $\lambda$, their lengths or the wave numbers are given as a constant $\beta = 2 \pi n_0 / \lambda$, where $n_0$ is the average refractive index of the photopolymer. The two incident beams interfere with each other and create a volume hologram.

We define the $k$ vector $\mathbf{k}$ as the wave vector extending in the direction of the interference fringes created by these two rays. These three vectors then satisfy:

$$\mathbf{n}_s = \mathbf{n}_r + \mathbf{k}. \quad (1)$$

Next, let us use this volume hologram to reproduce light. Let $\mathbf{n}_m$ be the wave vector of the incident light. Then, from the Bragg condition above, we can calculate the reconstructed light $\mathbf{n}_\text{out}$ as follows:

$$\mathbf{n}_\text{out}' = \mathbf{n}_m + \mathbf{k}. \quad (2)$$

In general, however, $\mathbf{n}_m$ does not align with $\mathbf{n}_r$. Due to this discrepancy, the naive prediction result $\mathbf{n}_\text{out}'$ is known to deviate from the observation and needs to be corrected:

$$\mathbf{n}_\text{out} = \mathbf{n}_m + \mathbf{k} + \Delta \mathbf{q}, \quad (3)$$

where $\Delta \mathbf{q}$ is a vector with the direction same as the surface normal. Its length is calculated so that $\mathbf{n}_\text{out}$ is placed on the circle with radius $\beta$. We define a vector $\mathbf{q}$ perpendicular to the surface with length $\beta$. The above equations only determine the output beam’s direction.

We are also interested in how much incoming light gets diffracted. The theory gives the diffraction efficiency $\eta$ as follows [29, 50]:

$$\eta = \left| v \sin \left( \sqrt{v^2 + \xi^2} \right) \right|^2, \quad (4)$$

$$v = \frac{\pi n_1 d}{\lambda \sqrt{R S}}, \quad \xi = \frac{|\Delta \mathbf{q}| d}{2 c S}, \quad (5)$$

$$c_R = n_m^2 q / \beta^2, \quad c_S = n_{\text{out}}^2 q / \beta^2, \quad (6)$$

where $c_R$ and $c_S$ are called the obliquity factors [50]. Note that $\theta$ is the incident angle of $\mathbf{n}_m$, $n_1$ is the refractive index modulation of the photopolymer, and $d$ is the photopolymer thickness (See also eq. (42, 43) in [50]).

As a special case, if there is no slant, i.e. the gratings are aligned with the photopolymer normal, and the input beam is ideal, i.e., $\mathbf{n}_m = \mathbf{n}_r$, then $\xi = 0$ and $c_R = c_S$. This simplifies the diffraction efficiency to the following as given as eq. (45) in [50]:

$$\eta = |v \sin(v)|^2 = \sin^2 v = \sin^2 \left( \frac{\pi n_1 d}{\lambda \cos \theta} \right). \quad (7)$$

3.3 Learned Computer-Generated Holography Pipeline

Our learned CGH pipeline builds upon state-of-the-art optimization methodology of hologram generation for dataset creation [23, 26, 44, 47, 56, 73, 84]. Firstly, we introduce this optimization method. Then, we will explain how our learned method differs from these methods and their learned derivatives. To our knowledge, our learned method is the first attempt towards generating 3D holograms only using RGB inputs but not RGBD inputs.

3.3.1 Hologram Dataset Generation

A HoloBeam projector generates multiplane images at the desired projection distance by optically relaying images generated close to an SLM. The optical relay here refers to the set of lenses used in front of an SLM as depicted in Fig. 1 layout. As ideally, the optics take care of relaying operation in HoloBeam, the remaining computational challenge is calculating the ideal hologram pattern, $O_h$, for a phase-only SLM to generate 3D images at various image planes $Z_0, Z_1, \ldots, Z_n$ in close vicinity of a SLM. This calculation could be achieved by propagating a hologram pattern, $O_h$, using a light transport model. Such a model could simply be written as a convolution operation [77]:

$$u(x, y, z) = O_h(x, y) + h(x, y, z), \quad (8)$$

where $u$ represents the complex amplitude at a target image plane, $z$ represents the distance between a hologram and a target image plane, and $h$ represents a convolutional kernel that simulates light transport. Note that $h$ could also be learned from actual hardware using camera captures [45], or could be replaced with a Convolutional Neural Network (CNN) [23] using these captures. The resultant intensity, $|u|^2$, could then be compared against a target image, $T$, using a loss function, $\mathcal{L}(|u|^2, T)$. Over a few successions of iterations, a hologram could be generated from target images dedicated to each plane $(T_0, T_1, \ldots, T_n)$. These target images are typically generated using an image or a photograph and their corresponding depth maps (e.g., [23, 44, 47, 84]).

3.3.2 Our Learned Method

Our learned CGH pipeline aims to produce multiplane holograms without requiring the scene’s depth information. Typical and conventional scenes or images often do not arrive with depth information. Although their depth information could be estimated reliably using a CNN [11], given the wide availability of 2D images and photographs, we see value in easing a user’s workflow in generating holograms...
def estimate(x, n):
    
    Parameters
    ----------
    x : torch.tensor
        Single color images [kx1xmxn].
    n : torch.nn.modulelist
        Network model used in training.
    
    Returns
    -------
    O_h : torch.tensor
        Estimated holograms [kx1xmxn].
    
    y = n.forward(x)
    a = y[:, 0]
    b = y[:, 1]
    \[ \phi[\cdot, \cdot, 0::2, 0::2] = a[\cdot, \cdot, 0::2, 0::2] \]
    \[ \phi[\cdot, \cdot, 1::2, 1::2] = a[\cdot, \cdot, 1::2, 1::2] \]
    \[ \phi[\cdot, \cdot, 0::2, 1::2] = b[\cdot, \cdot, 0::2, 1::2] \]
    \[ \phi[\cdot, \cdot, 0::2, 0::2] = b[\cdot, \cdot, 1::2, 0::2] \]
    \phi \rightarrow O_h
    return O_h

Listing 1: The learned differentiable model used in estimating multiplex phase-only holograms (Pythonic abstraction). This routine runs for every color primary separately.

without access to the depth information. This way, in the future, existing 2D digital content (e.g., games, movies) could potentially be converted to 3D holograms without having to go through multiple steps of estimating depth and generating holograms.

The optimizations discussed previously [23, 44, 47, 84] could be used to generate a hologram dataset from RGBD data. A hologram generation model could then be trained using RGB images as input while discarding their depth channel and their corresponding optimized holograms. Such a model could be trained and tested using the forward model found in Listing 1. In this forward model, a CNN could estimate an output with two channels from a single color of an input image.

In the meantime, we should note that holograms generating images in proximity to an SLM typically generated using the Double-Phase coding method [34, 59, 71]. Inspired by Double-Phase coding, these estimated output channels could then be compiled into a phase-only hologram pattern following a checkerboard-like pattern, maintaining the look of a Double-Phase coded hologram.

4 IMPLEMENTATION

This section will detail the making of HOE in our prototypes, our two prototypes used in our evaluations, and our learned CGH pipeline.

4.1 HoloBeam Thin Eyepiece

We used photopolymer sheets as the recording material for our HOE. Specifically, we used holographic film from Litiholo, a 2x3 inch plate consisting of a photopolymer applied to a 2.0 mm glass plate. The photopolymer consists of a 60-micron tri-acetyl cellulose (TAC) film substrate, a 60-micron recording layer, and a protective film layer. The total thickness, including the glass substrate, was 2.28 mm. In HOE recording, the reference and object beams hit the plate simultaneously. If these beams reach the same side of the plate, we obtain a transmissive HOE; if they reach from both sides, we obtain a reflective HOE.

In general, according to the principle of Bragg diffraction, a transmissive HOE requires a shallower diffraction structure than a reflective HOE. In other words, the design tolerance of the diffraction structure is larger for transmission HOEs, and they are more resistant to disruptions such as physical vibrations during fabrication.

Therefore, we adopted the transmissive design in this study. For ordinary AR display applications, reflective HOEs are more often used due to the advantages of stray light prevention, high transmission efficiency, and placement of the built-in display.

4.2 HoloBeam Prototypes

Amplitude-only HoloBeam Our amplitude-only prototype is built to demonstrate how compact, slim, and cost-effective our solution could be. This prototype uses a green laser diode with a 532 nm wavelength and 10 mW optical power. We harvested a laser diode from a generic laser pointer and drove it with an IRF540N MOSFET and an Arduino microcontroller. We collimate this coherent light with a 100 mm focal length lens, Thorlabs LA1509. The collimated beam then arrives at an amplitude-only SLM, specifically a Digital Micromirror Device (DMD) with 854 by 480 pixels and 5.4\(\mu\)m pixel pitch. This specific DMD is harvested from a pico projector, RIF 6 Cube, and we can only push 8-bit frames without any access to timing or individual binary frames.

The modulated beam from DMD is relayed to an image plane with a throw distance of 30 cm using 4f optics. Following the path from DMD towards our image plane, we use a 50 mm plano-convex lens, Thorlabs LA1131, an adjustable aperture at the Fourier plane, Thorlabs SM1D2D, and a 150 mm bi-convex lens, LB1437. This prototype has no beam steering capability and uses a fixed-focus HOE eyepiece at a location 30 cm away from the projection assembly. Fig. 5 shows the entire assembly of our amplitude-only HoloBeam prototype, and Fig. 7 shows an example see-through capture. As demonstrated in our supplementary materials, we could also build a vertical-layout assembly.

Phase-only HoloBeam We constructed our phase-only HoloBeam prototype to demonstrate a system with high image quality and a wide FoV (see Fig. 6). The prototype uses fiber-coupled light sources (420, 520, and 638 nm - Fisba ReadyBeam) and is also equipped with an incoherent RGB LED light source, which can be activated as needed. The phase-only SLM in our prototype is a Jasper Display SLM Research kit (2400 by 4094 pixels and 3.74\(\mu\)m...
pixel pitch). The modulated beam from the SLM generates multi-
planar images after passing through a 4f system and reflecting off a
mirror used for path folding (Thorlabs ME1-P01). From the SLM to
the path folding mirror, we used the following optical components:
an achromatic lens (Thorlabs AC254-100A-ML), an aperture located
at the Fourier plane (Thorlabs SM1D12D), and another achromatic

We project the reconstructed multiplane image to an eyepiece us-
ing a 2f system consisting of Thorlabs AC254-150-A-ML. Although
there is an optional galvanometer scanner (AT20-2278) available,
we did not utilize it in this work. At a meter throw distance, our
user perceives multiplane images by looking through our eyepiece
composed of two lens cascades. From the projection toward the user,
these lenses in our eyepiece are Thorlabs LA1384 and Thorlabs
LA1050. For more details, please consult our supplementary.

Figure 6: Phase-only HoloBeam prototype. A fiber-coupled multicolor
light source illuminates a phase-only SLM. Multiplane images gener-
ated from this SLM are filtered with a pinhole using an aperture and
a 4f imaging system. These images are then projected at a meter
distance using a 2f imaging system as a projection lens. Note that
an XY scanner follows the projection lens to steer the beam toward a
user. A user wearing an eyepiece composed of a cascade of lenses
perceives images with multiple focuses. The distance between the
projector assembly and the eyepiece is a meter in reality and not
drawn at the actual scale to avoid a wider figure.

Figure 7: An actual photograph of a see-through image from our
amplitude-only HoloBeam prototype. The insets demonstrate how the
generated virtual image is focused at a far plane (1.5 meters away).

Figure 8: Captured photographs from the eyebox of our phase-only
HoloBeam prototype. These photographs are captured using a XIMEA
MC245MG-SY-UB image sensor equipped with an adjustable 5 – 50
mm lens while using 20 ms exposure times. During these captures, only
a green LED light source is used in the display prototype. The figure
also shows zoomed-insets and their target images. The provided
images are circular as the aperture of our eyepiece in this prototype
is circular. The source image on the right side is from DIV2K [2].

4.3 HoloBeam Software

We choose to dedicate our amplitude-only prototype to showcasing
thin eyepieces. Thus, this particular prototype relies on projecting
conventional 2D images to deliver its message related to form factor
(not amplitude-only holograms). In the meantime, we dedicate our
phase-only prototype to delivering 3D images while providing a
wide FoV and large throw distances. We choose not to use HOE in
the phase-only prototype to avoid the heavy engineering work that
poses an engineering resource challenge (e.g., recording HOE in
multicolor, replicating optics of the display for the reference beam
of a recording setup).

Our learned CGH pipeline is simply dedicated to our phase-
only prototype, and it bases on PyTorch [65] and a CGH toolkit
GitHub:complight/multiholo [7]. Training of our learned CGH pipeline is conducted
using a learning rate of 0.0001 for ten epochs (Source code:
GitHub:complight/multiholo [7]). Our model relied on a U-Net [69] with 28 hidden channels as our neural network. To generate
our dataset for training our learned CGH pipeline, we first create
depth maps for the DIV2K image dataset [3] following the work by
Aksit et al. [8,44] (plane separation is 1 mm). We resize these images and their
depth to the resolution of our SLM. Using their estimated depth, we
use these images to generate multiplane holograms with six planes
following the work by Aksit et al. [8,44] (plane separation is 1 mm).
We discard the estimated depth, and we use 900 input images and their
corresponding multiplane holograms in our training while 100
of them are in validation. As the training complete, our estimation
routine takes about 20-28 ms to generate a single phase-only holo-
gram at the resolution of our SLM. We use a computer with NVIDIA
GeForce RTX 2080 GPU with 12 GB memory and an Intel i7, 3.9
GHz CPU to drive our holographic display prototype. When we
display our holograms in our phase-only prototype, we update the
calculated \( O_h \) with a linear phase grating term to avoid undiffracted light,

\[
O_h(x, y) = \begin{cases} 
  e^{-j(\phi(x,y) + \pi)} & \text{if } y = \text{odd} \\
  e^{-j\phi(x,y)} & \text{if } y = \text{even}
\end{cases}
\]

\[ (9) \]

where \( \phi, x, y \) represents the original phase of \( O_h \). In Listing [1]
we provide a simplified learned estimation model that used in our
training and estimation routines. Note that the estimation routine
relies on a CNN. Specifically, we use a U-Net as our CNN [69]. This
CNN takes a single color of an image as input. The output of the
CNN is a tensor with two channels. The resultant constrained tensor
represents the phase component of a phase-only hologram. During a training session, the output of this estimation model is compared against a ground-truth hologram using an L2 loss function. Unlike the recent literature [23], no reconstruction losses are involved.

5 EVALUATION

Using our two HoloBeam prototypes, we assess the practical limits of our approach. For analyzing the optical quality of our HoloBeam approach, we use our phase-only prototype, whereas for the demonstration of a slim eyepiece built using an in-house recorded HOE, we will use our amplitude-only prototype.

5.1 Quality Analysis

In this section, we will rely on optimized phase-only holograms for assessing absolute resolution and FoV characteristics of our proposed method. For demonstrating, 3D images from our prototype, we will rely on both our learned method and optimization method.

Resolution and Field of View. The eye relief of our phase-only prototype is 35 mm. The aperture of our eyepiece is 50.8 mm, leading to FoV of 70 degrees as depicted in Fig. 1. We also provide additional results from various scenes in Fig. 8. To assess the resolution quality of this prototype, we rely on a standard Modulation Transfer Function (MTF) analysis [17]. Across our evaluations, we capture photographs with a XIMEA MC245MG-SY-UB image sensor and an adjustable 5–50 mm lens while using 20 ms exposure times to approximate a human observer’s experience. Our MTF analysis suggests that the phase-only HoloBeam prototype can support up to 24 cpd in resolution when used with LED illuminations (at central FoV). A healthy Human Visual System (HVS) demands 30 cpd or more for realistic-looking resolutions. Such resolutions could be met as we use the existing lasers in our phase-only HoloBeam prototype. However, we observe that perturbing fringe patterns shadow the image quality as depicted with an extra capture at our supplementary materials. We believe these perturbations mostly originated from optics starting from the end of 4f lenses towards the eyepiece. HoloBeam could potentially provide higher resolutions while using LEDs with the increasing aperture size of SLM and lenses in the future.

Multiplane Images. Light source coherency used in a holographic display dictates the depth of field of the reconstructed images [58]. Thus, incoherent broadband sources increase the depth of field and degrade optical focus cues in reconstructed images. Given the situation with the depth of field of images, the conventional way to demonstrate multiple images in a holographic display involves using a laser light source. We also use laser in our phase-only HoloBeam prototype to demonstrate capabilities related to multiplane images.

However, as the lenses between our 4f system and eyepiece generate unintended aberrations and distortions, our final image contains fringes when lasers are used (see our supplementary document for evidence). These distortions could be fixed in the future using learned approaches that could account for imperfections in holographic display hardware [20, 23, 45] and by designing and manufacturing dedicated projection optics like in many projector products. Thus, to avoid any visual artifacts caused by the eyepiece and additional lenses, we capture reconstructions of our phase-only holograms right after the 4f imaging system using a bare XIMEA MC245MG-SY-UB image sensor with 50 ms exposure. We provide a sample capture demonstrating a focus change as in Fig. 10. Note that the optimized version shown in Fig. 10 resembles the image quality of most recent standard literature [23, 44, 73]. For more results, please consult our supplementary materials.

In our observation, the learned model shrinks the depth range of a scene (e.g., six multiplane images mostly focused at two planes) and tends to distribute depth levels that are not faithful to an original depth map (e.g., windmills door becoming sharp at near focus rather than far focus in Fig. 10). We believe this learned model promises encouraging first results towards a hologram generation routine where a 2D image is transformed into a 3D multilayer hologram without requiring scene-depth information or multiple perspective images.

5.2 HOE Lens Analysis

In HoloBeam, the spatial relationships among the projection system, the eyepiece, and the eye affect the final image quality and visibility. This section analyzes our HOE design with simulations that mimics our amplitude-only prototype.

Simulation Setup. In our simulation on MATLAB 2022a, we use an open-source ray optics library. Since this library does not implement HOE simulations, we implemented a volume hologram class based on Sec. 3.2. For all simulations, we set the wavelength to $\lambda = 532$ nm, the average refraction index to $n_0 = 1.5$, the maximum refractive index modulation to $n_1 = 0.04$, and the photopolymer thickness $= 30 \mu m$, respectively.

Figure 11 shows the layout of our simulation. We used the library’s default eye optics parameters for the eye model, and the pupil diameter was set to 3 mm. The eyeball center is set to 30 mm from the HOE lens. We assume that the projection optics relays a...
virtual image from the amplitude-only SLM and the virtual image forms at 150 mm from the HOE with a pan angle of 35 degrees. The HOE is designed to form a lens with f=150 mm and a 35-degree angle tilt. Note that we scaled the virtual image size by 3, assuming that the projection optics relay the SLM image plane, leading to the pixel pitch of the relayed image as $p = 5.4 \times 3 = 16.2\mu m$. This results in the rays’ diffraction angle from each pixel forming $2\sin(1.22a/p)$, about 4.6 degrees. We randomly generated 100 rays for each pixel along the central ray direction within the diffraction angle.

We also assume an ideal projection system that can guide images to the default pupil center position. We thus let the central rays target the center of the HOE, i.e., (0,0,0) in the world coordinates. We refer to this positional relationship as the default layout. As a displayed image, we set 17x17-point grids uniformly spanning in an 801x801 pixel image (Fig. 12 left column top).

We evaluate two major factors related to misalignments: the eyebox and head alignment. The eyebox analysis evaluates when the eye locations change while the virtual image source and the eyepiece are fixed. The head alignment analysis evaluates when the head system, i.e., the HOE eyepiece and the eye, changes its orientations and positions against the virtual image source.

We set the disturbance ranges of each setup in the following. For the eyebox position: ±4 mm with 0.25 mm step in the x-y directions; for the head orientation: ±10 degrees with 0.5-degree step for the pan-tilt angles; and for the head translation: ±4 mm with 0.25 mm step in the x-y directions.

For the eyebox and head translation analyses, one may also explore the z direction. We, however, fixed the z-axis parameter in our analyses to keep the explanations concise since our pilot analysis results did not give much difference in the z-axis analysis compared to the x-y space analyses.

Simulation Results Figure 12 shows an overview of our simulations, where the second to fourth rows correspond to eyebox analysis (x-y plane), head orientation analysis (pan-tilt angles), and head translation analysis (x-y plane), respectively. The second column shows the total brightness of the observed images for the given misalignment parameters. The total brightness is relative to that of the image taken with the default layout, i.e., the center pixel of each figure. The third column is a color visualization of whether or not the light rays hit the retina at each viewpoint. The images accumulated hit from every 10 viewpoints over the misalignment parameter space. And the rays from the same viewpoint will be the same color regardless of their intensity. The fourth columns instead accumulate ray brightness and show colormaps of the total brightness of all given view conditions. Please also refer to our supplementary viewpoint videos of the three analyses.

The eyebox analysis shows that the brightness level is consistent over eye position changes. This is understandable given that the diffraction angle of the virtual image is about 4.6 degrees, which sufficiently covers the pupil, as we can also observe in Fig. 11.

The head orientation analysis shows that our setup is more robust in the pan (horizontal) rotation than in the tilt (vertical) orientation. A possible reason for this tendency is that the HOE lens is designed for input rays’ virtual point source to be placed on the x-z plane; thus, the diffraction efficiency could radically decrease (off-Bragg) along vertical angle errors.

Finally, the head translation analysis shows that our setup is more robust in head translation errors than head orientation errors. However, the image intensities change periodically along vertical head misalignment. The image thus may appear to flicker in dynamic tracking environments, depending on the tracking accuracy. This tendency may stem from the periodical structure of the Bragg diffraction efficiency over input angles, as in Fig. 5. Our informal, practical observation with the amplitude-only prototype aligns with the simulation results.

6 Discussion and Limitations

Beaming Displays [39] design methodology aims to resolve a vital issue in AR glasses designs and enable practical AR applications that could converge to comfortable and realistic AR experiences. Although HoloBeam provided evidence that Beaming Displays designs could provide resolutions and FoV meeting more of HVS demands, there are still outstanding major issues related to Beaming Displays design methodology. We list these issues and their potential solutions in the following paragraphs.

Eyebox and cost Holographic approaches imply small eyebox traditionally, and also true for our implementation. Most recently, the work by Jang et al. [40] addresses the eyebox issue while maintaining a true 3D holographic AR glasses, which could help inspire a fix of the issue. Holographic displays lead to a complex hardware design that is highly costly due to niche equipment such as a phase-only SLM [85]. Our amplitude-only prototype aims to improve on cost of holographic displays by relying on cheaper but less capable hardware. However, this is not a true fix to the cost problem as cheaper alternatives for a phase-only SLM have to be invented.

Improving mobility. Beaming Displays [39] provided evidence that delivering images to a moving user could be possible to some extent, however, HoloBeam does not provide any tracking of users and the same case is not replicated as HoloBeam focuses on improving image quality and form factor. The original Beaming Displays work tends to relay an image on a screen integrated into an eyepiece, whereas HoloBeam is a standalone optical relay that magnifies images projected in mid-air. Thus, HoloBeam is much less forgiving of any misalignment in the beaming path. We believe this requires special attention in future works and the functionality of a diffuser in the original Beaming Displays has to be embedded into future variants HoloBeam to benefit from both mobility and image quality improvements.

If the functionality of a diffuser could be transferred to a new eyepiece design, we trust that mobility-related issues (e.g., head position and orientation of a user) could be resolved without sacrificing the form factor. This item is our next step in this line of research.

Improving the eyepiece. The image brightness provided by a HOE eyepiece is sensitive to misalignments due to users’ head orientations. We believe there are potential research directions that could help mitigate these alignment-related issues. A potential solution could be to investigate embedding the trends in curved or free-form HOE designs [37, 81, 82] into our HOE designs in the future. Another potential research direction is to bring the prototype of bird-bath optics used in the original Beaming Displays [39] into the HOE design space. In such a case, we could explore the embedding properties of a diffuser with a lens in HOE designs [37, 81, 82].

HoloBeam’s target applications. Given the limitations in tracking and alignment for HoloBeam, we identify applications that could make the most sense for what is possible with HoloBeam.
today. Applications that do not require a user to be frequently moving could be more forgiving with the lack of tracking. Thus, we believe HoloBeam could be a good fit for work-related applications (e.g., desktop displays). There are existing 3D desktop displays for similar purposes (e.g., Brelyon[1]), which we believe HoloBeam could provide a new slim version. A potential application area in the future could also be automotive displays, namely heads-up displays. Note that a driver in a car is more or less stationary and must constantly gaze at the road. A future variant of HoloBeam could provide more freedom in movement and could be a potential new way to build a heads-up display that does not require fiddling with the windshield or dashboard of a car.

Improving Depth Generation of Learned CGH method. The depth generation of our learned holograms is limited as the depth information of a scene is not provided as an input to our learned algorithm. We designed our learned algorithm as a single constrained U-Net. However, a depth estimation network could also be used to condition our method or a more detailed analysis could be conducted in the future regarding the contribution of each layer in that single U-Net. This way, an educated way to improve our attempts could be achieved in the future.

Complementing contact lens AR. In recent years, there has been a push in research related to AR contact lenses [70], which could potentially transform AR to a seamless setting without any glasses. In the future, our work could also be transformed into an optical component embedded in a contact lens that helps register beams from a projector to a user’s retina.

7 CONCLUSION

Future AR glasses must be thin and lightweight while supporting high resolutions, wide FoV, and optical focus cues. Today’s AR glasses struggle to balance these requirements, often yielding to design challenges. However, the experts largely agree that these requirements are compulsory to maintain comfortable visual experiences with AR glasses. So, we ask whether the way out of this struggle could lie in changing the perspectives in AR glasses design. This paper introduces a new stand leading to a bold change in AR glasses design which we named HoloBeam. For the first time in the literature, we demonstrate very slim AR glasses based on our HoloBeam method. These AR glasses support 3D images with near-correct optical focus cues and provide resolutions matching commonly accepted retinal resolution criteria (30 cpd). In this design, there are still open research issues that require proper attention from the relevant research communities. These issues include tracking the accuracy of users beam, accuracy of projectors and designs, leading to more freedom in user movement. Although these outstanding issues exist, this work is a significant milestone that could pave the road to a new body of work toward the ultimate AR glasses with comfortable and realistic visual experiences.

SUPPLEMENTARY MATERIAL

Our code is available at [GitHub:complight/multiholo]. Dependencies are available at [GitHub:kaanaksit/odak][43][46]. Additional media, results and materials are distributed separately as a supplementary documents.

ACKNOWLEDGMENTS

The authors wish to thank Koray Kavakli for fruitful discussions. Kaan Aksit is supported by the Royal Society’s RGS\[R2\],212229 - Research Grants 2021 Round 2 in building the hardware prototype and Meta Reality Labs inclusive rendering initiative for building the rendering pipeline. Yuta Itoh is supported by JST FOREST Grant Number JPMJFR206E and JSPS KAKENHI Grant Number JP20J14971, 20H05958, and 21K19788, Japan.

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Supplementary Materials for “HoloBeam: Paper-Thin Near-Eye Displays”

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1 Contributions from each author

Here we list contributions from each author in this specific research work:

Yuta Itoh:

• Designing and building a HOE recording setup in hardware.
• Compiling extensive study on HOE design space.
• Compiling figures for HOE recording setup and functional test of recorded HOEs.
• Review and edits for the entire documentation.

Kaan Aksit:

• Initiation of project idea of HoloBeam, this includes blueprints for projector designs, conventional eyepiece designs and algorithmic designs.
• Design and manufacturing of amplitude-only and phase-only HoloBeam prototypes,
• Coding and training of the machine learning model.
• Writing abstract, introduction, related work, conclusion sections entirely.
• Compiling figures for a simplified layout diagram of HoloBeam, teaser, phase-only and amplitude-only hardware in the manuscript and supplementary documentation.
• Review and edits for the entire documentation.

2 Additional Related Works

2.1 Thin Relay Optics for Augmented Reality Glasses

Holographic Optical Elements There are various photosensitive materials for holograms [14]. For example, Silver halide emulsions are used for amplitude modulating Holographic Optical Element (HOEs). Yet another example, Photorefractive crystals (dichromate gelatin or lithium niobate) and photopolymers are organic materials used for phase modulating HOEs. Among these materials, photopolymers are relatively easy to handle because they do not require the development process required for other materials and can be bleached by incoherent light. Attracting attention as a replacement for HOEs, metasurfaces are artificial sub-wavelength subwavelength structures promising superior optical performance, for example, large aperture, wide bandwidth, and polarization dependence [9, 10]. However, these systems are in their early stages in proving their practicality in Augmented Reality (AR) glasses.

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Figure 1: Vertically built amplitude-only HoloBeam prototype. Our projection assembly’s optical path is folded using two mirrors in this configuration.

2.2 Augmented Reality Glasses

Beaming AR Glasses. Most recently, a new design method called Beaming Displays [6] is proposed, where active components are separated from AR glasses designs to address issues in conventional AR glasses providing a fixed focus image. In their work, a user wears bird-bath optics similar to the ones in the literature, and the image is projected into this bird-bath optics from a distance. However, their results [6] demonstrate a moderate Field Of View (FoV), limited resolutions, and bulky form factor with no support in optical focus cues. Our work follows the design approach in Beaming Displays in AR glasses. However, HoloBeam merges the benefits of holographic techniques with Beaming Displays. This way, HoloBeam improves upon Beaming Displays by supporting optical focus cues, improved resolutions and unmatched form-factors.

Other AR approaches. We do not cover all other AR displays approaches in the literature that may have a loose relevance to our work [3]. Both previous literature [6] and HoloBeam share similarities with projection based spatial AR displays such as head-up displays in automotive [4]. The primary difference in our approach with projection based spatial AR displays is that the eyepiece is close to a user’s eye. Although there are AR displays having eyepiece close to a user’s eye [8], unlike theirs our solution do not require a large projection screen. Thus, HoloBeam brings the possibility to widen FoV and making displayed images visible only to a user wearing our eyepiece. In recent years, there has been a push in research related to AR contact lenses [12], which could potentially transform AR to a seamless setting without any glasses. We understand that such contact lenses based approaches pose primary challenges in practical aspects and approvals. In the future, our work could also be transformed into an optical component embedded in a contact lens...
that helps register beams from a projector to a user’s retina. Thus, 

HoloBeam has the potential to be complementary to the contact lens
based AR designs of the future.

3 AMPLITUDE-ONLY HoloBeam prototype

Our amplitude-only HoloBeam prototype could also be built in a
vertical layout as demonstrated in Fig. 1. This way, we demonstrate
that our projection assembly could be assembled in various forms
using optical path folding (e.g., with mirrors or prisms). Such
path folding could be helpful when integrating HoloBeam to an
automotive application in a potential future.

It should also be noted that we provide sample photographs from our benchtop prototype in Fig. 2.

4 PHASE-ONLY HoloBeam prototype

Additional photographs from our phase-only HoloBeam prototype
are provided in Fig. 3.

5 OPTICAL BEAM PROPAGATION

A phase-only hologram is described as a two-dimensional array filled
with phase values and typically described with a complex notation
as \( O_h = e^{j\theta(x,y)} \), where \( \theta \) represents the phase delay introduced
by each pixel in a phase-only hologram. Holographic displays typically
represent holograms, \( O_h \) with programmable SLMs. Meanwhile,
a coherent beam illuminating a phase-only hologram, \( U_i \), is also
described as a two-dimensional array. Note that \( U_i \) is an oscillating
electric field described as \( U_i = A_0 e^{j(kx+\phi(x,y))} \), where \( A_0 \) represents the
amplitude of the optical beam, \( k \) represents the wavenumber that
can be calculated as \( \frac{2\pi}{\lambda} \), \( \lambda \) represents the wavelength of light, and
\( \phi \) represents the initial phase of the optical beam. In calculation, \( A_0 \)
is often considered \( A_0 = 1 \) for an ideal collimated beam, while \( \phi \)
is assumed to be a two-dimensional array filled with random values
between zero to \( 2\pi \). Finally, leading to simplification of \( U_i \) as \( e^{j\phi} \).
In simple terms, as \( U_i \) illuminates \( O_h \), \( U_i \) by modulated with \( O_h \),
forming a new modulated beam \( U_m \) that is calculated as
\[
U_m = U_i O_h = e^{j(\phi(x,y)+\phi(x,y))},
\]
A modulated beam, \( U_m \), has to propagate in free-space from the
hologram plane (SLM plane) towards a target depth plane to
reconstruct images at various depth planes. Propagation of optical
beams from one plane to another follows the theory and method
introduced by Rayleigh-Sommerfeld diffraction integrals [5]. This
diffraction integral’s first solution, the Huygens-Fresnel principle, is
expressed as follows:
\[
u(x,y) = \frac{1}{j\lambda} \int \int u_0(x,y) e^{jkr} \cos(\theta) dxdy,
\]
where resultant field, \( U(x,y) \) is calculated by integrating over every
point across hologram plane, \( U_0(x,y) \) represents the optical field
in the hologram plane for every point across XY axes, \( r \) represents
the optical path between a selected point in hologram plane and a
selected point in target plane, \( \theta \) represents the angle between these
points. The angular spectrum method, an approximation of the
Huygens-Fresnel principle, is often simplified into a single convolu-
tion with a fixed spatially invariant complex kernel, \( h(x,y) \) [13].
\[
u(x,y) = u_0(x,y) * h(x,y) = \mathcal{F}^{-1}(\mathcal{F}(u_0(x,y)) \mathcal{F}(h(x,y))).
\]
In our implementations, we rely on a fundamental library for optical
sciences [2] , which provides a differentiable version of various
optical beam propagation methods. Therefore, our methods can
work with other beam propagation approximations.

6 ADDITIONAL RESULTS FROM PHASE-ONLY HoloBeam
prototype

In this section, we provide additional results from the eyebase of our
prototype. Fig. 4 depicts the effect of using coherent and incoherent
illumination sources in the phase-only HoloBeam prototype.

Fig. 5 demonstrates a full color image reconstruction using our
phase-only HoloBeam prototype. Please note that this demonstrator
does not have color distortion correction implemented, yet. There-
fore, in Fig. 5, readers will observe color distortions and misalign-
ments in the final image.

Fig. 6 provides additional capturing results from our phase-only
HoloBeam prototype, demonstrating the image quality.

For more results from our prototypes, please consult to provided
compressed files that contains videos and raw photographs from our
experiments.

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Figure 3: Additional photographs from our phase-only HoloBeam prototype. Images shows a true scale assembly and close look up at the projector assembly. Cooler fan in this hardware setup helps keeping the Phase SLM stable at a fix temperature. In a final product, these components are not necessarily needed, and there are much custom compact holographic projectors in some existing products (e.g., Holoeye).

Figure 4: Photographs from the eyebox of the phase-only HoloBeam prototype. (Left) A photograph showing the resultant reconstructed image when a single color of the laser is used. (Middle) A close-up view from the very same scene shown in the left image. (Right) A photograph showing the resultant reconstructed image when a single color LED is used. Lasers cause unintended perturbations in the image as demonstrated in this figure, while LEDs lead to a smoother image. Note that these photographs were taken using a smartphone camera.

Figure 5: Photographs from the phase-only HoloBeam prototype. Full color photographs from our HoloBeam prototype. Note that full color images do not have the correct distortion correction in-place, thus leading to aberrated images.

Figure 6: Resolution Quality of phase-only HoloBeam prototype. The first row shows captured photographs from the eyebox of our phase-only HoloBeam prototype. These photographs are captured using a XIMEA MC245MG-SY-UB image sensor equipped with an adjustable 5 – 50 mm lens while using 20ms exposure times to approximate a human observer’s view. During these captures, only a green LED light source is used in the display prototype. The second row shows zoomed-insets from the first row, while the third row shows the target images. The provided images are circular as the aperture of our eyepiece in this prototype is circular. The image quality of our phase-only HoloBeam approximates the ground truth images with a slight loss in contrast. The source image in the second, third and fourth column are from Big Buck Bunny [11], DIV2K [1] and Changil et al. [7], respectively.