Towards zero-th order free, full field of view, computer generated holography

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ABSTRACT

In this study, we investigate the removal of zero-order diffraction (ZOD) in computer-generated holography (CGH) using a destructive interference approach. Our method addresses the common issue of non-modulated light, which manifests as a bright spot at the center of virtual images, by generating a counter-phase light pattern. We demonstrate that our approach can achieve up to $86 \pm 2\%$ reduction in ZOD intensity across various holographic techniques, including Fourier and Fresnel transform holography. This method ensures constant alignment, does not compromise the modulation depth of Spatial Light Modulators (SLM), and is computationally efficient. Our findings pave the way for more effective integration of CGH in augmented reality applications, particularly in near-eye displays, by providing clearer and more accurate virtual images.

Keywords: Spatial light modulators (SLMs), Computer generated holography (CGH), Zero-th order diffraction (ZOD), Augmented reality (AR)

1. INTRODUCTION

Phase-only CGH is employed in different applications, including beam shaping,[1] data storage, 3D photostimulation for optogenetics,[2] Optical manipulation,[3] and 3D imaging for Augmented Reality (AR).[4,5] Among these, 3D imaging for AR has gained significant relevance due to the increasing interest in Augmented Reality applications for NEDs, driven by the numerous benefits offered by laser-based phase-only CGH.

The adoption of CGH for 3D virtual images in AR can potentially eliminate the vergence-accommodation conflict,[6] a major challenge currently faced by the scientific community. Furthermore, thanks to new algorithms and devices, CGH can provide aberration-free, high-resolution images and enable real-time holographic videos. Such aspects combined with the high brilliance of laser light can have a relevant impact on next-generation NEDs.

Although holographic technology is considered the ultimate 3D display approach[5] and can deliver realistic virtual images, many obstacles still need to be overcome. These include the significant computational effort required to compute holograms, as well as the limitations of devices that modulate light.

In particular, among other limitations, spatial light modulators (SLMs) used in holographic displays are pixelated devices, and, as such, they cannot modulate all the light that impinges on them. Indeed, the portion of light hitting the inter-pixel regions is reflected back specularly, resulting in an unwanted bright spot at the center of any virtual image produced by the SLM.

The mentioned non-modulated light is a common problem even in advanced research and implementations[5] and is usually removed in various ways. The most common method involves placing an obstructive target in the center of the Fourier plane (2f) of a 4f telescope, acting as a high-pass filter. However, this approach requires a bulky 4f system, incompatible with miniaturized AR devices, and results in a dark spot in the virtual image plane.

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Alternative approaches involve shifting the projected light away from the ZOD position, either laterally or axially. However, lateral displacement limits the effective field of view and reduces the diffraction efficiency, introducing comatic aberrations into the projected light pattern.[7] The axial displacement causes the ZOD to shift significantly out of focus from the computed image, but the imposed quadratic phase relevantly reduces the modulation depth of the device and further complicates the setup.

Recent works have demonstrated ZOD suppression through destructive interference approaches, utilizing two-photon excitation in combination with aberration-based techniques. However, the inherent non-linearity in these methods enhances the suppression effect and often require complex optical setups, making them less suitable for compact AR applications and limiting their scalability.[8,9]

In this work, we propose a new approach based on destructive interference between the modulated light pattern and the non-modulated one coming from interpixel regions, proving experimentally that it is possible to reduce ZOD intensity by up to 86 ± 2% without loss in the hologram field of view and without requiring a 4f telescope. The method is based on the generation of a virtual image having a bright spot in the ZOD position, with opposed phase compared to the non-modulated bright spot. With this interferometric approach we can remove the unwanted ZOD from the pixelated display without inserting any major drawback and addressing any kind of CGH approach. This method ensures constant alignment and only removes light that does not belong to the image, even when the designed hologram projects a significant amount of light at the ZOD location.

2. METHOD

Light impinging on the SLM is split in a modulated and a non-modulated component. The non-modulated component is reflected by the SLM as if it were a conventional mirror. The modulated light undergoes a spatial modification of its phase and/or amplitude and produces a virtual image as a result of its propagation. Its characteristics will depend on the precise phase pattern displayed. In the case of Fourier transform Holography, the virtual image is formed at the spatial frequency domain plane, where the ZOD is focused in a bright spot. In the case of Fresnel propagation instead, modulated light is focused in an arbitrary distribution in three dimensions, while the non-modulated component propagates as a collimated beam. In both cases, the irradiance of the ZOD is usually much brighter than that of the virtual image. Indeed, even tough current SLMs allow for fill factor as high as 93% as in the case of the used PLUTO-2.1 LCoS Spatial Light Modulator, all the light coming from the inter pixel regions is collected in one single spot. In this study, we propose to utilize a portion of the modulated light, referred to as a corrective beam, which has the same intensity as the ZOD but an opposite phase, to effectively cancel out the ZOD To do so, we calculate holograms as interference of two phase patterns: the hologram that delivers the desired virtual image ($\Phi_{V_i mage}$) and the phase pattern of a bright spot that is responsible for the removal of the ZOD (Φ_{ZOD-r}). In our approach $\Phi_{V_i mage}$ can be computed with any existing approach,[10] and Φ_{ZOD-r} is computed independently. The overall phase pattern to be uploaded onto the SLM can be written as:

$$\Phi_{SLM} = angle(A_1 \cdot e^{-i\Phi_{V_i mage}} + A_2 \cdot e^{-i\Phi_{ZOD-r}}), \tag{1}$$

If we consider the presence of the non-modulated light, the overall phase at the spatial light modulator plane is:

$$\Phi_{SLM} = angle(A_1 \cdot e^{-i\Phi_{V_i mage}} + A_2 \cdot e^{-i\Phi_{ZOD-r}} + B \cdot e^{-i\Phi_{ZOD}}) \tag{2}$$

Therefore, to achieve interferometric ZOD removal, it is necessary to match the amplitude A_2 of the corrective beam (ZOD-r) to the amplitude B of the ZOD. This leads to the following system of equations:

$$\begin{cases} (A_2)^2 = B^2, \\ \\ \frac{(A_2)^2+(A_1)^2+B^2}{B^2} = \frac{I_{tot}}{I_{ZOD}}, \end{cases} \tag{3}$$

where, I_{tot} is the overall intensity of the source, while I_{ZOD} is the one of the ZOD. Solving the above system leads to the following result:

$$A_1 = B \cdot \sqrt{\frac{I_{tot}}{I_{ZOD}} - 2} \tag{4}$$

This last relation between the amplitude of the virtual image and that of the ZOD implies that full ZOD removal is only possible if the overall modulated intensity is at least twice that of the ZOD. This condition is easily met by modern phase-only SLMs.

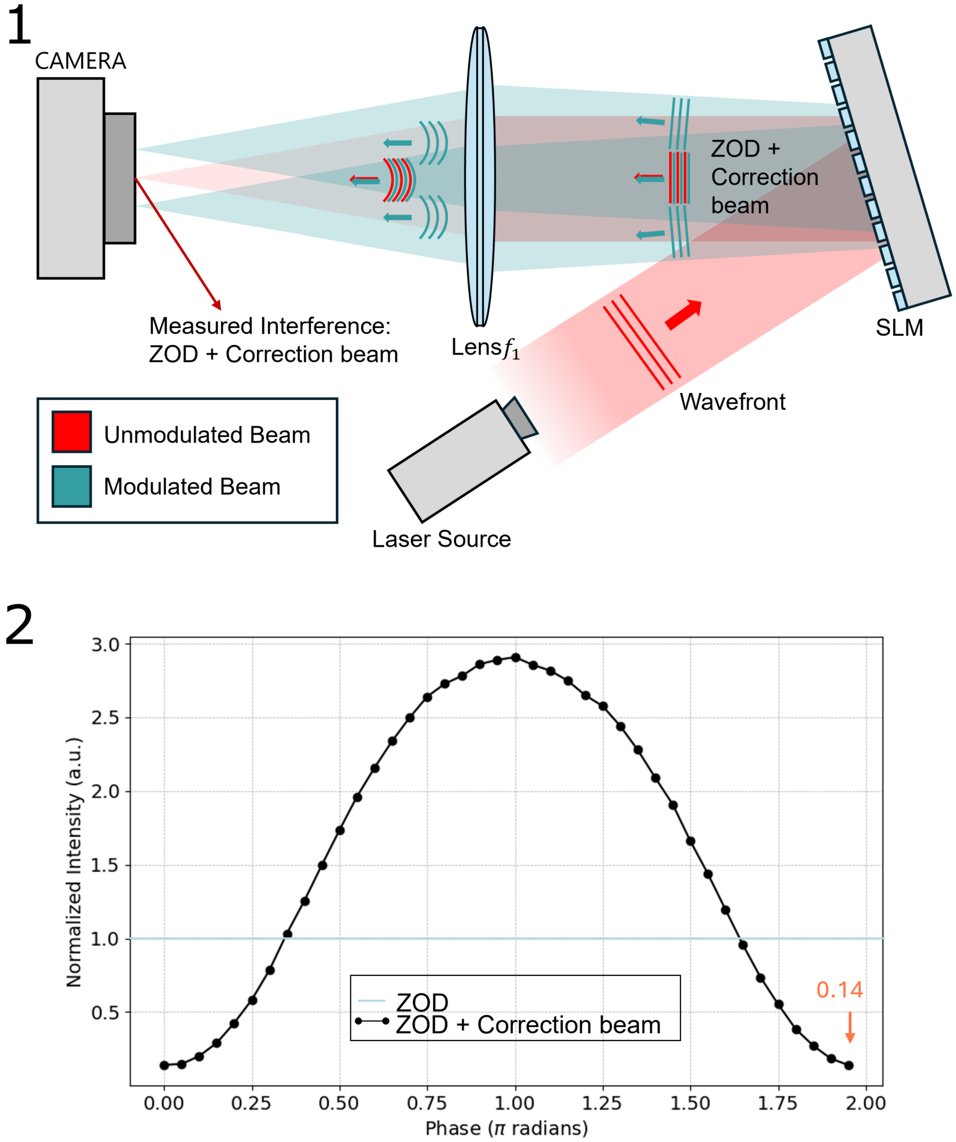

Figure 1. **Method** 1.Schematic of the 2f Setup employed. The Interfering intensity is measured on camera with a ROI of (15x15 pixels) around the ZOD position. 2. Measured intensity of the ZOD spot as a function of the correction beam phase delay.”adapted from (Towards zero-th order free, full field of view, computer generated holography), under review”.

For a given experimental setup, the values of I_{tot} and I_{ZOD} can be experimentally measured by projecting a hologram with zero intensity at the ZOD location and measuring the output with a camera. From these values, a rough estimate of A_1 and A_2 can be calculated. Once A_1 and A_2 are found, it is necessary to find the value of Φ_{ZOD-r}, which is measured by modulating its value linearly until the intensity of the ZOD is minimized, as shown in the experimental data in Fig.1, panel 2.
Once the optimal phase value has been found, it is possible to finely determine the values of A_1 and A_2 by iterating over a small set of their values around the ones estimated with (1).

The setup employed to test the effectiveness of our ZOD removal method, shown in fig.1, panel 1, consists in a 2f system using a 20 cm focal distance lens (ACT508-200-A-ML, Thorlabs, USA) with the SLM (PLUTO 2.1, Holoeye, Germany) in its back-focal plane, and the camera (Panda 4.2, PCO, USA) in its front-focal plane. The light source is a single mode laser (C-FLEX, HÜBNER Photonics, Germany) at 532 *nm*, collimated by a single lens (AC254-050-A-ML,Thorlabs, USA) and cropped by an iris (IDA25/M, Thorlabs, USA) to match the size of the SLM. In this way the camera displays the spatial frequency content of the light modulated by the SLM device, and in particular the ZOD is a bright spot at its center. By projecting a hologram with zero intensity at the ZOD location, B can be estimated from the total intensity of a small central area of the camera, and A_1 from the total intensity of the remaining pixels.

3. RESULTS

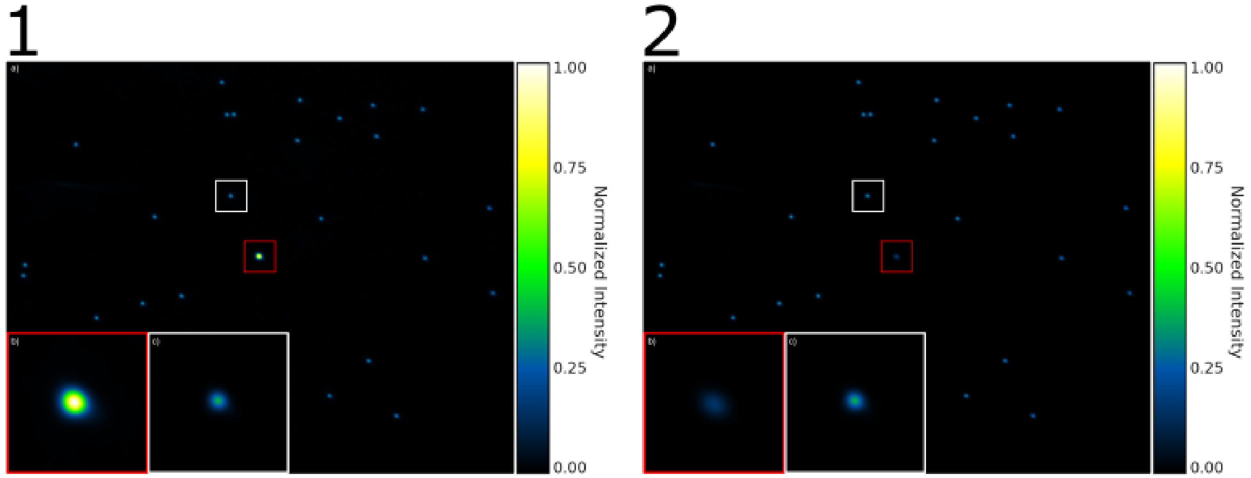

Figure 2. **Results** 1. Point-cloud hologram before the correction. (a) shows the full point-cloud hologram, (b) provides a magnified view of the ZOD region, and (c) offers a close-up of a reference point within the virtual image. 2. Point-cloud hologram after the correction, with the same normalization of panel 1. (a) shows the full point-cloud hologram, (b) provides a magnified view of the ZOD region, and (c) offers a close-up of a reference point within the virtual image.”adapted from (Towards zero-th order free, full field of view, computer generated holography), under review”.

In order to prove the effectiveness and versatility of our method, we measured the destructive interference for several Fourier-transform holography and across different holographic techniques. Our results consistently demonstrated that approximately $86 \pm 2\%$ of the intensity of zero-order diffraction (ZOD) can be removed in all the scenarios examined.

To visually assess the impact of the ZOD reduction, in Figure 2, panels 1 and 2, we show a comparative analysis of two point-cloud holograms with and without the proposed correction, i.e. the amplitude and phase parameters that maximize the destructive interference between the two beams. The hologram consists of 30 randomly distributed points in the Fourier plane. The points were all positioned in a single plane to facilitate evaluation of the results, but performance of the removal method remains the same in the case of three-dimensional point cloud holograms.

In the uncorrected image, the ZOD is significantly brighter than the reference point, highlighting the challenge of integrating a holographic-based system into an AR NED without an effective suppression mechanism. In contrast, the corrected image shows a substantial reduction in ZOD brightness, with the ZOD now appearing much dimmer than the reference point. The ZOD is only visible due to the use of a custom color scale, and is otherwise imperceptible to the human eye when the hologram is projected with appropriate light intensity. Notably, the reference point remains visibly unchanged in both images, demonstrating that the correction process does not compromise the integrity of the hologram. This selective reduction in ZOD intensity enhances the overall clarity and quality of the holographic image, underscoring the effectiveness and potential of our method.

4. DISCUSSION

The removal of ZOD through a destructive interference approach is of significant relevance for several reasons. Firstly, the applied phase delay remains consistent across different holograms, which ensures that the modulation depth of the Spatial Light Modulator (SLM) is not compromised. Secondly, the computation of the phase pattern is both straightforward and computationally efficient, facilitating rapid implementation in practical applications. Additionally, the interfering system is always inherently aligned since both beams originate from the same display and follow the same optical path, making it a robust approach to achieve ZOD removal.

However, the intensity of the ZOD can slightly depend on the specific hologram, necessitating the estimation of coefficients A_1 and A_2 in advance without relying solely on intensity optimization. This pre-estimation process enhances the robustness and predictability of the approach, ultimately improving its integration for actual applications.

The calculations and demonstrations presented in this study are based on a monochromatic laser at 532 nm. Extending the proposed method to full-color rendering for RGB wavelengths requires addressing certain considerations. First, calibration must be performed for the longest wavelength, and the grey values corresponding to a 2π phase shift for shorter wavelengths should be calculated based on this calibration.

In future work we aim to investigate the source of the remaining $14 \pm 2\%$ intensity of the ZOD. In particular it could be due to either the presence of phase aberrations between the modulated and non-modualted light, or to the need of a non-uniform phase calibration of the SLM over its area.

By gaining a deeper understanding and better control over the destructive interference process, this approach has the potential to greatly improve the quality and sharpness of holographic displays, particularly in applications like augmented reality near-eye displays (AR NEDs), pushing the boundaries of holographic display technology.

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REFERENCES

[1] Piccardo, M., de Oliveira, M., Policht, V. R., Russo, M., Ardini, B., Corti, M., Valentini, G., Vieira, J., Manzoni, C., Cerullo, G., and Ambrosio, A., “Broadband control of topological–spectral correlations in space–time beams,” *Nature Photonics* (2023).

[2] Pozzi, P., Maddalena, L., Ceffa, N., Soloviev, O., Vdovin, G., Carroll, E., and Verhaegen, M., “Fast calculation of computer generated holograms for 3d photostimulation through compressive-sensing gerchberg–saxton algorithm,” *Methods and Protocols* **2**, 2 (2018).

[3] Grier, D., “A revolution in optical manipulation,” *Nature* **424**, 810–816 (2003).

[4] Manu Gopakumar, Gun-Yeal Lee, S. C. B. C. Y. P. J. K. . G. W., “Full-colour 3d holographic augmented-reality displays with metasurface waveguides,” *Nature* **629**, 791–797 (2024).

[5] Changwon Jang, Kiseung Bang, M. C. B. L. . D. L., “Waveguide holography for 3d augmented reality glasses,” *Nature Communications* **15**, 66 (2024).

[6] Yijie Pan, Juan Liu, X. L. Y. W., “A review of dynamic holographic 3d display: algorithms, devices, and systems,” *IEEE Transactions on Industrial Informatics* **12**, 1–1 (2015).

[7] Palima, D. and Daria, V. R., “Holographic projection of arbitrary light patterns with a suppressed zero-order beam,” *Applied Optics* **46**(20), 4197–4201 (2007).

[8] Hernandez, O., Guillon, M., Papagiakoumou, E., and Emiliani, V., “Zero-order suppression for two-photon holographic excitation,” *Optics Letters* **39**(20), 5953–5956 (2014).

[9] Yu, H., Ren, S., Xuan, H., and Wang, Y., “Performance improved for two-photon multi-focus microscopy based on a spatial light modulator by eliminating the zero-order beam,” *Optics Express* **32**(17), 29483–29493 (2024).

[10] Dapu Pi, J. L. and Wang, Y., “Review of computer-generated hologram algorithms for color dynamic holographic three-dimensional display,” *Light: Science Applications* **11**, 231 (2022).