Implementation of Computer Generated Holograms in a low-cost phase-only Spatial Light Modulator for modulation of the spatial distribution of light

Andrés Arias,* Juan C. Rojas-Velasquez,† and Alejandra Valencia‡
Laboratorio de Óptica Cuántica, Universidad de Los Andes, Colombia

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In this work, we demonstrate the implementation of Computer Generated Holography (CGH) using a low-cost, phase-only Spatial Light Modulator (SLM) to control the spatial distribution of light. Employing theoretical frameworks for both complex field generation and intensity pattern reconstruction, we developed and tested algorithms suitable for the SLM's limited phase modulation range. We successfully generated Laguerre-Gauss modes and their superpositions, as well as arbitrary intensity distributions such as the university mascot image, using both analytical methods and iterative Fourier algorithms. Our experimental results validate the feasibility of using low-cost SLMs for precise optical field modulation despite hardware limitations. This approach offers an accessible and flexible alternative for holographic applications in optical traps, microscopy, lithography, quantum computing and photonics.

I. INTRODUCTION

The generation of a desired optical field is of special interest in many different areas of physics, chemistry and life sciences. Arbitrary fields are generally fabricated via holography, in which a specific pattern is recorded into a diffractive element to produce a desired output field [1]. Traditionally these patterns are recorded in special holographic films made of acetate, which makes modifying the pattern tedious and time consuming. In recent years, Spatial Light Modulators (SLMs) have become an extremely attractive topic in diverse areas of optics given their ability for the generation of on demand arbitrary optical fields. These devices allow us to modulate both amplitude and phase of an incident light beam, in a process known as Wavefront Shaping [2].

To do this, we seek to calculate the corresponding hologram that recreates a desired field when we input it in the SLM. This is known as Computer Generated Holography (CGH). There are several methods to calculate CGHs, that depend on what variables the specific SLM can control; Be it phase, amplitude or both simultaneously [3–8]. In this work, we present a method for controlling both amplitude and phase of an optical field with an SLM that only modulates phase, with the method of complex amplitude modulation [4] and a method to generate intensity patterns using phase reconstruction algorithms [9].

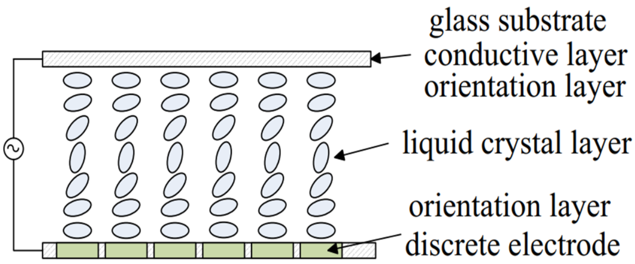


Figure 1: Enter Caption

II. THEORETICAL FRAMEWORK

A. Spatial Light Modulators

Spatial Light modulators are composed of a series of layers of liquid crystals whose orientations can be changed depending on an external voltage . Most commonly, they are composed of twisted nematic (TN) microdisplay cells, in which the liquid crystals exhibit birefringence, making the refractive index in one axis higher than the other [2, 10]. Thus, by progressively changing the orientation of each layer, the relative phase of the light beam can be modified. This means that the light reflected of the SLM acquires a phase $\psi(x, y)$ that can be loaded into the SLM:

$$E_{SlM}(x, y) = E_{in}(x, y)e^{i\psi} \quad (1)$$

B. Generation of Complex fields.

In general, to recreate an arbitrary complex field, it is necessary to modulate both the amplitude and phase of the incident light. Nevertheless, it is much more convenient to work with phase only elements, given their wider availability.It is then necessary to design a phase only func-

* Email:a.arias@uniandes.edu.co
† Email:jc.rojasv1@uniandes.edu.co
‡ Email:ac.valencia@uniandes.edu.co

tion that reproduces the desired complex field. This can be achieved by recreating the desired complex field in an specific diffraction order. Amplitude modulation is done by diffracting more or less light to the zeroth diffraction order, which lets us change the amount of light in the higher diffraction orders [7].

To recreate the complex field, we follow the procedure described by Bolduc *et al.* [4]. Consider we want to recreate in the first order of diffraction a complex field of the form:

$$E_{\text{out}}(r,z) = \mathcal{A}(r,z)\exp\left(i\Phi(r,z)\right). \tag{2}$$

We imprint the incoming light beam with a general phase of the form:

$$\Psi(m,n) = \mathcal{M}(m,n)\text{mod}\left(\mathcal{P}(m,n) + 2\pi m/\Lambda + 2\pi n/\Lambda, 2\pi\right) \tag{3}$$

where m and n are the horizontal and vertical numbers of pixels of the SLM's screen, Λ is the period of the diffraction grating (We use a diagonal grating to facilitate the isolation of the first diffraction order), $\mathcal{M}(m,n)$ is a function of $\mathcal{A}(m,n)$ and $\mathcal{P}(m,n)$ is a function of $\mathcal{A}(m,n)$ and $\Phi(m,n)$. This is to be a more general form of more traditional kinoforms, holograms which are made with the interference of the desired output field with an angled plane wave [1](recovered if we set $\mathcal{M}(m,n) = 1$ and $\mathcal{P}(m,n) = \Phi(m,n)$) . The first order term of the Taylor expansion of the field after phase modulation is:

$$T_1(m,n) = -\frac{\sin(\pi\mathcal{M}(m,n) - \pi)}{\pi\mathcal{M}(m,n) - \pi} e^{i(\mathcal{P}(m,n) + \pi\mathcal{M}(m,n))} \tag{4}$$

Since we want this to be equal to our desired field, we find that the exact solutions to recreate the field in the first order of diffraction are:

$$\mathcal{M}(m,n) = 1 + \frac{1}{\pi} sinc^{-1}(\mathcal{A}(m,n)) \tag{5}$$
$$\mathcal{P}(m,n) = \Phi(m,n) - \pi\mathcal{M}(m,n) \tag{6}$$

Where $sinc^{-1}(x)$ is the inverse of $\sin x/x$. Numerical inversion of the sinc function is very computationally intensive, so approximate solutions are preferred. In this work, we choose the functions:

$$\mathcal{M}(m,n) = \mathcal{A}(m,n)/\max(\mathcal{A}(m,n)) \tag{7}$$
$$\mathcal{P}(m,n) = \Phi(m,n) - \pi\mathcal{M}(m,n) \tag{8}$$

Which when inserted into equation 3 give the phase only holograms used to generate the desired beam in the first order. A grayscale image of these holograms with values 0-255 is what is sent to the SLM.

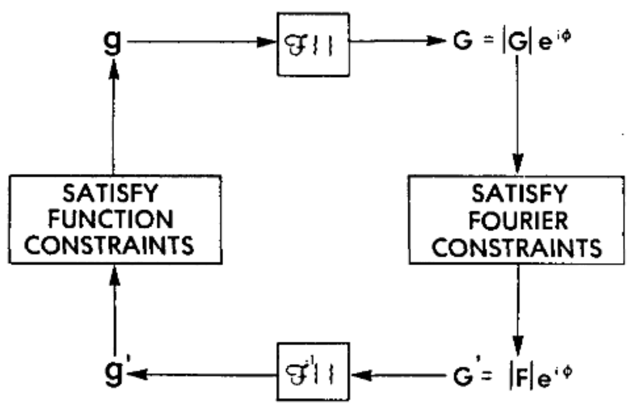


Figure 2: Block diagram of the iterative Fourier Algorithm to generate the phase patterns.

C. Generation of Intensity patterns

The previous method relies heavily on the phase of the desired field. For this reason, it is inadequate if the desired output is given by an intensity pattern, where all phase information is lost. A way to solve this problem is by using the Fourier transforming properties of lenses.

Given we know two intensity measurements in planes which are related by a Fourier transform, an appropriate phase can be constructed such that the Fourier transform of the complex field in the phase modulation plane gives a field with the desired intensity in the Fourier plane [11].

The phase pattern to be loaded in the SLM can be found by iterative applications of the Fourier transform between the two planes. Quantitatively, the algorithm is as follows [9]:

$$G_k(u) = |G_k(u)|\exp\left[i\phi_k(u)\right] = \mathcal{F}\left[g_k(x)\right], \tag{9}$$
$$G'_k(u) = |F(u)|\exp\left[i\phi_k(u)\right], \tag{10}$$
$$g'_k(x) = |g'_k(x)|\exp\left[i\theta'_k(x)\right] = \mathcal{F}^{-1}\left[G'_k(u)\right], \tag{11}$$
$$g_{k+1}(x) = |f(x)|\exp\left[i\theta_{k+1}(x)\right] = |f(x)|\exp\left[i\theta'_k(x)\right] \tag{12}$$

We start the algorithm in the second step (eq. 10) by setting $|F(u)|$ the magnitude of the desired intensity pattern at the Fourier plane and ϕ_k a random phase. Then we take the Fourier transform and after switch the intensity of the Fourier transform with the intensity at the SLM plane $|f(x)|$, in our case a plane wave. to conclude the algorithm we Fourier transform back to G_{k+1}. This is repeated until convergence of the phase terms ϕ_k and θ_k. the parameter θ_k is the desired phase pattern to be sent to the SLM.

In practice, a modified version of this algorithm was used, which guarantees faster convergence via gradient descent methods [9, 12].

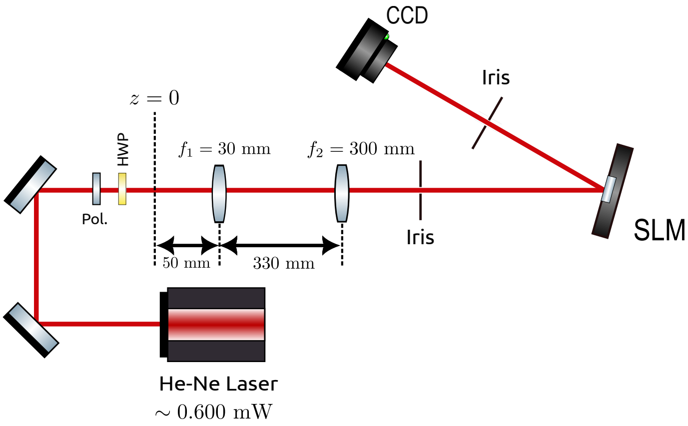


Figure 3: Optical setup for the generation of complex fields. The setup to generate intensity patterns is identical except that the second iris must be changed to a lens in a $2f$ configuration.

III. OPTICAL SETUP

The setup shown in Figure 3 is used for generating complex optical fields. A He-Ne laser (633 nm) is used as light source with around 0.6 mW of power. Then, as the SLM uses a definite polarization, the light beams pass through a polarizer and a Half Wave Plate (HWP). After, the beam passes through a telescope system conformed by f_1 and f_2 which collimates and increases the size of the light beam. The light is filtrated by the iris and then reflected by the SLM, on which a hologram is projected.The beam now passes through another iris so higher diffraction orders are filtered and then it is measured with a CCD Camera.

The setup for generating intensity patterns is identical, except that the second iris is changed by a lens in a $2f$ system to take the Fourier transform optically.

IV. EXPERIMENTAL RESULTS AND CONSIDERATIONS

A. Generation of Complex fields

To implement the holograms experimentally, there are a few important considerations that must be taken into account. First, it is crucial that the holograms are smaller than the total size of the beam illuminating the SLM; This also makes aligning the incident beam so that it strikes the entirety of the hologram easier. This is why we used a $10x$ telescopic system to ensure we illuminate the entirety of the SLM screen.

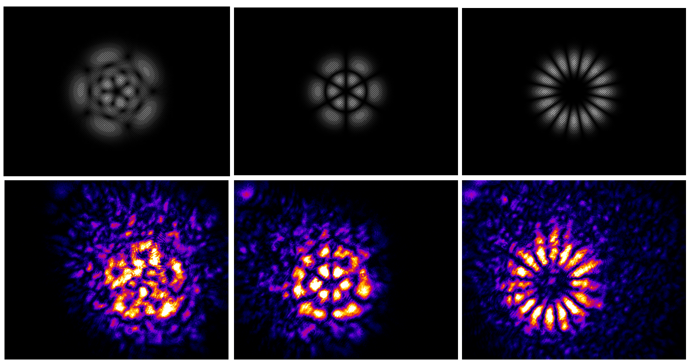
Additionally, the spatial isolation of the first order may be difficult because of its proximity and dimness compared to the zeroth order. It is important to chose a diffraction grating that is sufficiently frequent so that the orders separate enough to make isolation possible, but not frequent enough that we encounter resolution limitations with the SLM. We found that using a period Λ of ~ 0.8 the pixel size of the SLM works best.

On the other hand, the angle at which the SLM is tilted should be as small as possible to reduce any errors caused by asymmetric lighting.

The most import consideration however, is that in practice, most SLMs do not modulate phase up to 2π, and ones that do tend to be inaccessible expensive for most labs. In our case, we used a a low- cost Spatial Light Modulator (SDE1024, Cambridge Correlators), with resolution 1024×768 and a pixel pitch of $9 \times 9\mu m$. This particular model has a maximum phase modulation of around 0.6π according to the manufacturer. There is a way to somewhat correct the errors caused by the inability to fully modulate phase, that is by introducing a "Contrast" parameter that makes the pixel values of the hologram closer to the values that the SLM actually displays [13]. The corrected (Grayscale) pixel values take the form:

$$\Psi(m,n)_{new} = Floor[Clip(0, C(\Psi_{Old} - 255/2) + 255/2, 255)] \quad (13)$$

Where C is our contrast parameter, $Clip(0, x, 255)$ is a function that returns 0 if $x \leq 0$ and 255 if $x \geq 255$ and $Floor(x)$ is a function that returns the integer part of x. A value of $C = 1$ doesn't change the pixel values, $C = 255$ gives us a binary pattern and $1 < C < 255$ gives us a "Ramp" pattern. In our experiments we used a value of $C = 2.5$ as this seemed to give the best results.



$LG_1^3 + LG_2^{-2}$ $\quad$ $LG_1^3 + LG_1^{-3}$ $\quad$ $LG_0^8 + LG_0^{-8}$

Figure 4: Results obtained for the generation of the superposition of Laguerre-Gauss modes. The figure shows the holograms projected on the SLM (first row) and their corresponding image measured with the CCD camera. A contrast of $C = 2.5$ was used for all the images

We tested the holograms by making Laguerre-Gauss modes of light, and superpositions of them. The LG_p^ℓ mode is generated by the expression:

$$E(r,\phi,z) = C_{lp}^{LG}\frac{1}{w(z)}\left(\frac{r\sqrt{2}}{w(z)}\right)^{|l|}\times \\ \exp\left(-\frac{r^2}{w^2(z)}\right)L_p^{|l|}\left(\frac{2r^2}{w^2(z)}\right)\times \\ \exp\left(-ik\frac{r^2}{2R(z)}\right)\exp(-il\phi)\exp(i\psi(z)) \quad (14)$$

Where L_p^l are the generalized Laguerre polynomials and C_{lp}^{LG} is a normalization constant.

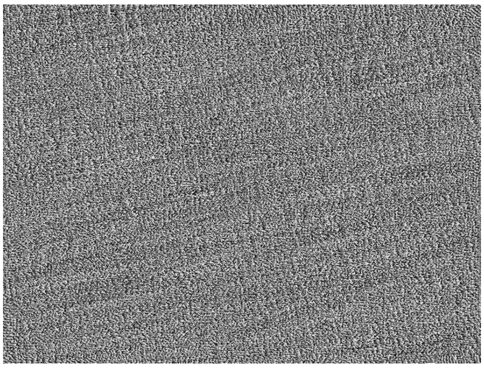
Figure 4 shows results obtained, images captured by a CCD Camera and their corresponding hologram projected on the SLM. Images obtained with the camera match with those expected by theory.We can see that small details like the ones in Figure 4a are not clearly resolved.This is product of the fact that the method used is approximate, and the limitations of resolution and phase modulation from the SLM. It is quite likely that a sharper image could be generated by a systematic search for optimal values of contrast, and the utilization of the numerically calculated "Exact" hologram.

B. Generation of intensity patterns

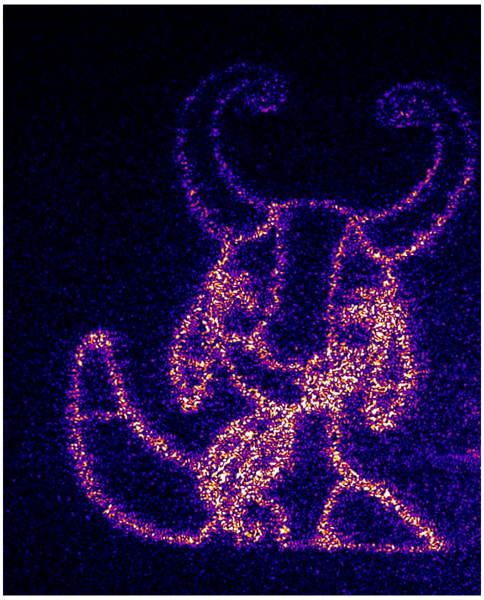
We calculated the corresponding phase pattern for the university´s mascot, Seneca the goat, using the algorithm described previously and implemented with the python library "Diffractsim" [12] which facilitates the calculation of diffraction and light propagation with the angular spectrum method.

To generate the image, a lens with a focal length of $150mm$ was used. This gives an image of $\sim 300\mu m$ which was an ideal size to capture with a CCD camera.The size of the final image can be adjusted by changing the focal length of the imaging lens, so that the image can be arbitrarily large or small depending on the needs of the experiment.

Figures 5a and 5b correspond to the calculated phase pattern and the image captured in the CCD respectively. The phase pattern can be understood as the sum of the corresponding diffraction grating needed to generate each point, each with a unique spacing and orientation. The details in the image are decently well resolved near the Fourier plane, although the low resolution of the SLM limits finer details, specially as the image cant be centered because of the generation of a bright zeroth order diffraction spot, which washes out the fainter image. Better results are obtained if the image is symmetric to mirroring in both axis, as a mirrored copy of the original image is generated because of the negative frequencies that appear in the Fourier transform.



(a) Phase pattern calculated with the iterative Fourier algorithm.



(b) CCD image of the light distribution at the Fourier plane.

Figure 5: Results obtained with the iterative Fourier method to generate the intensity pattern of the university's mascot Seneca the goat. In this case we used a contrast of $C = 2.5$

V. CONCLUSIONS

This work presents a viable methodology for generating both complex optical fields and arbitrary intensity patterns using a low-cost phase-only SLM. Despite the hardware limitations, such as the restricted phase modulation range of $\sim 0.6\pi$, we achieved effective modulation by applying phase correction techniques, including a tunable contrast parameter. The experimental generation of Laguerre-Gauss modes and recognizable intensity images confirms that the proposed approximations and algorithms are sufficiently robust for practical applications.

Our implementation underscores the potential of low-cost SLMs in educational and research environments, especially where access to high-end optical components is limited. Additionally, the open-source code provided facilitates reproducibility and further development. Future improvements could focus on optimizing phase reconstruction algorithms and SLM calibration techniques to enhance image fidelity and resolution.

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CODE AVAILABILITY

The codes used in this work are available open access:

- *This code generates holograms for Laguerre Gauss modes and sends them to the SLM as a second screen.It includes an interface to dynamically change the parameters of the beam:*

  `https://github.com/andresarias1105/Proyecto_SLM/blob/main/LG_HOLOGRAMS.ipynb`

- *This code generates holograms for an arbitrary field given you know the function of the field.There are also other methods for making holograms based on Fourier optics and phase reconstruction algorithms:*

  `https://github.com/andresarias1105/Proyecto_SLM/blob/main/SLM_HOLGRAMS.ipynb`

- *This code generates the hologram for a* $N \times N$ matrix of gaussian beams:

  `https://github.com/andresarias1105/Proyecto_SLM/blob/main/Matrix_Hologram.ipynb`