Hologram optogenetic illumination with a few pixel SLM

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ABSTRACT

A novel CGH algorithm is proposed for targeted neural stimulation using a few pixel Spatial Light Modulator (SLM) device. This is achieved with the elaboration of standard CGH design algorithms to include a regularized cost function for the discretization of phase and amplitude. The regularized cost function is appropriate for designing holographic masks that can be realized using a few pixel SLM. It is anticipated that these results will contribute to the research efforts towards a portable *in vivo* optogenetic system.

Keywords: hologram design, optogenetic illumination, regularizers, SLM

1. INTRODUCTION

Optogenetics is a novel technique for the precise control of neuronal activity using light. The potential of optogenetics for spatially precise neuronal activation has generated intense research throughout the optogenetics chain from light-sensitive proteins, gene delivery and expression to light illumination of genetically-modified neurons and recording of induced brain activity. In the multidisciplinary optogenetics scenery, optical illumination techniques for the stimulation of neurons play a key role. There are already a plethora of light delivery strategies that have been demonstrated primarily in *in vitro* optogenetic experiments.[1,2] Holographic optogenetic illumination using Computer Generated Holographic (CGH) phase masks has proved a fair compromise between efficiency and practicality that allows optogenetic stimulation of single or multiple neurons. The CGH phase masks are usually loaded on SLMs that modulate the phase of an incident light beam in order to generate the desired illumination pattern. Following the demonstration of optogenetic principles *in vitro*, the research community is gradually turning its attention to *in vivo* optogenetic applications. Miniaturization of the optogenetics hardware is an one-way solution towards practical *in vivo* optogenetic implementations for the study of the brain and even therapeutic purposes. It is the illumination part of the optogenetic apparatus that is impacted most by the requirement for compactness, since most of the present day optogenetic light delivery systems have a large footprint.[3] Apart from the obvious required advances in the hardware itself, proper algorithmic strategies are needed that accommodate the constraints of the potential miniaturized optogenetics technology. Here, we propose a novel design algorithm that utilizes a regularized optimization approach for efficient optogenetic holographic designs that are based on smaller size few pixel SLMs.

2. METHODOLOGY

In our study, an optogenetic stimulation system, that is possibly more appropriate for *in vivo* excitation, is simulated using Fourier Optics. Conventional SLM devices have a resolution of the order of 1024×1024 pixels, which, in turn, has a detrimental impact on the device size. Here, the simulated optogenetic system involves a *few pixel* SLM device combined with Computer Generated Holography (CGH) generating the desired illumination pattern for targeted neural photostimulation. In terms of Fourier Optics, we have utilized a free space propagation model using Fourier Optics Operators (Figure 1), as described in,[4] in order to simulate light travelling from the few pixel SLM device to the targeted reconstruction plane (Figure 2).

The miniaturized SLM device is simulated as a rectangular grid of a few pixels, of the order 10×10. Holographic masks, namely CGHs, are designed by optimizing a proper cost function via the use of the Gradient

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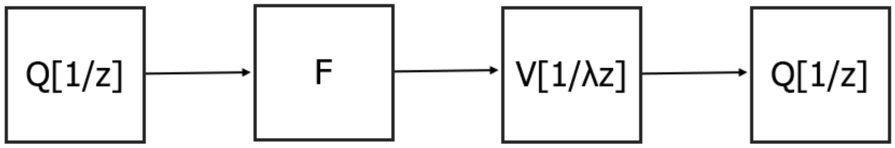


Figure 1. Free space propagation described via Fourier Optics Operators. The operators are applied (from left to right) onto the light field at the SLM plane, where z is the distance that light travels and λ the wavelength of each light source of the few pixel SLM device.

Descent (GD) algorithm.[5] The employed cost function involves both a term that captures the accuracy of the desired intensity response, as well as a term to account for a limited number of possible phase levels that can be represented by the few pixel SLM device. It is assumed that the miniaturized SLM device is capable of reconstructing multi-level amplitude and phase holographic masks. In general, we follow an approach similar to the method proposed in,[6] but with two significant modifications: (a) The SLM device considered here has a limited number of pixels, and (b) each pixel is capable of both amplitude and phase modulation.

We consider a few pixel SLM device having K pixels along the x axis, and L pixels along the y axis, in a rectangular arrangement. We denote as $(x_{k,l}, y_{k,l})$ the coordinates of the center of each pixel, where $k = 1 \dots K$ and $l = 1 \dots L$. Also, we denote as $A_{k,l}$ the intensity of pixel k, l, and $\phi_{k,l}$ its phase. We assume that each pixel generates a Gaussian light beam, so that the light field at the SLM plane can be modeled as

$$I(x,y) = \sum_{k=1}^{K} \sum_{l=1}^{L} A_{k,l} \cdot \exp\left(-\frac{(x - x_{k,l})^2 + (y - y_{k,l})^2}{2\sigma^2} \right) \cdot \exp\left(j\phi_{k,l} \right) \ , \tag{1}$$

where the parameter σ determines the so-called waist of the Gaussian beam, assumed here equal for all pixels. We also consider that $I(x, y)$ is the input to an optical system that generates the output light field $O(x, y) \in \mathbb{C}$, as described by the relation

$$O(x,y) = H\left\{ I(x,y) \right\} \ , \tag{2}$$

where the function $H\{\cdot\}$ describes the optical system under study. In the simulations given in this work, we have considered the optical system depicted in Fig. 2, which corresponds to free space propagation from the miniaturized, few pixel SLM device to the targeted reconstruction plane.

The output light field $O(x, y)$ is a function of the input light amplitudes $A_{k,l}$ and the phases $\phi_{k,l}$, of each pixel. Given a *desired response* output intensity field $D(x, y) \in \mathbb{R}^+$, the optimal values $A^*_{k,l}$ and $\phi^*_{k,l}$ for the parameters $A_{k,l}$ and $\phi_{k,l}$ are given as the solution to the following optimization problem

$$\left\{ A^*_{k,l}, \phi^*_{k,l}(x,y) \right\} = \arg \min_{A_{k,l}, \phi_{k,l}} \left(d\left(\left|O(x,y)\right|^2, D(x,y) \right) \right), k = 1 \dots K, \ l = 1 \dots L \ , \tag{3}$$

where $d(\cdot, \cdot)$ denotes some suitable distance/cost function, for example, the mean square error (MSE) or any other, more elaborate, cost function as in.[7] In this work, considering that due to technological limitations, the phases $\phi_{k,l}$ of the pixels are not allowed to take any value, but rather, a limited number of q equidistant phase levels can only be represented, we employ a regularized cost function similar to that proposed in.[6] In particular, we employ the cost function

$$d\left(|O(x,y)|^2, D(x,y) \right) = \frac{1}{N^2} \sum_{x=1}^{N} \sum_{y=1}^{N} \left(\left|O(x,y)\right|^2 - D(x,y) \right)^2 + \frac{1}{K \cdot L} \sum_{k=1}^{K} \sum_{l=1}^{L} \frac{\lambda}{2^\rho} \left(\sin\left(q \cdot \phi_{k,l} + \frac{3\pi}{2} \right) + 1 \right)^\rho \tag{4}$$

where the first part captures the accuracy of the illumination, while the second part favors phase values close to the phase levels that can be represented. It should be mentioned at this point that a similar term for limiting the possible values for the intensities $A_{k,l}$ could also be considered, to expand the scope of our approach so that technology limitations for the possible intensity levels are also modeled. This extension is the subject of ongoing work.

More details on the regularized cost function can be found in.[6] The optimization procedure is performed in an iterative fashion using the Gradient Descend (GD) algorithm. The algorithm generates the estimates $\boldsymbol{\phi}^{(n)}$ and $\boldsymbol{A}^{(n)}$ at the n-th iteration. In particular, for the problem considered here, the algorithm consists of the following two equations

$$\boldsymbol{A}^{(n+1)} = \boldsymbol{A}^{(n)} - \gamma_A \nabla_A d(\boldsymbol{\phi}, \boldsymbol{A}) \ , \tag{5}$$

$$\boldsymbol{\phi}^{(n+1)} = \boldsymbol{\phi}^{(n)} - \gamma_\phi \nabla_\phi d(\boldsymbol{\phi}, \boldsymbol{A}) \ , \tag{6}$$

where the vector $\boldsymbol{\phi}$ contains all the $K \cdot L$ phase variables and vector $\boldsymbol{A}$ contains all the $K \cdot L$ amplitude variables of our optimization problem. Also, γ_A and γ_ϕ are proper positive step size parameters.

3. RESULTS

A CGH that generates the alpha letter reconstruction image was designed, according to the procedure described in Section 2. The number of iterations of the GD algorithm was set to 100. Each light source of the few pixel SLM emitted light of wavelength 450 nm. The pixel grid of the simulated SLM device was 8 $\times$ 8. The size of each pixel of the miniaturized SLM device was 6 μm and the pixel pitch was 7 μm.

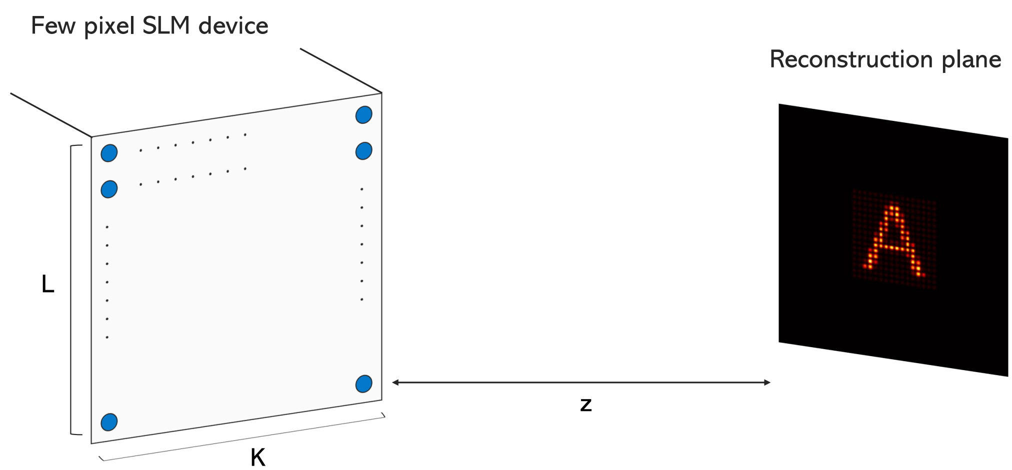
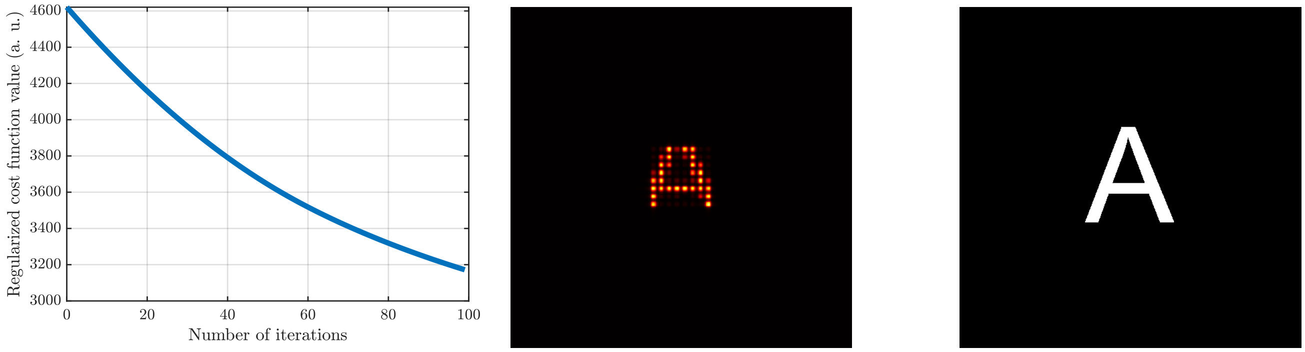


Figure 2. Layout of the few pixel SLM device. K and L are the number of pixels in the horizontal and vertical direction respectively. The light field emitted by the few pixel SLM travels a propagation distance z to the reconstruction plane.

The results of the design algorithm are shown in Fig 3. After 100 iterations, the regularized cost function (Fig 3(a)) converged to the optimal holographic mask. Fig 3(b) shows the reconstruction of designed 64 binary pixel phased mask for the target image of Fig 3(c). The reconstructed image is a pixelated version of the desired intensity response, as expected since the number of pixels of the SLM device is quite low. However, the alpha letter illumination pattern is well defined, thus the few pixel SLM device provides an efficient intensity response. We have chosen a very small number of pixels in order to highlight the effectiveness of the proposed approach and it is apparent that the reconstruction image quality scales with number of pixels. This is shown in Fig 4 for 16 $\times$ 16 pixels and Fig 5 for 32 $\times$ 32 pixels. In both cases for 100 iterations the algorithm yields a holographic mask whose reconstruction is improved with the number of pixels, yet still pixelated. Interestingly, the scaling of chosen number of pixels (16 $\times$ 16 and 32 $\times$ 32 pixels) does not lead to considerable gains in terms of reconstructed image quality. Obviously, the choice of the number of pixels is a trade off between the desired hologram reconstruction quality and the footprint of the SLM.



a b c

Figure 3. (a) Regularized cost function after 100 iterations. (b) reconstruction image by the 8 × 8 few pixel SLM device, (c) desired intensity response.

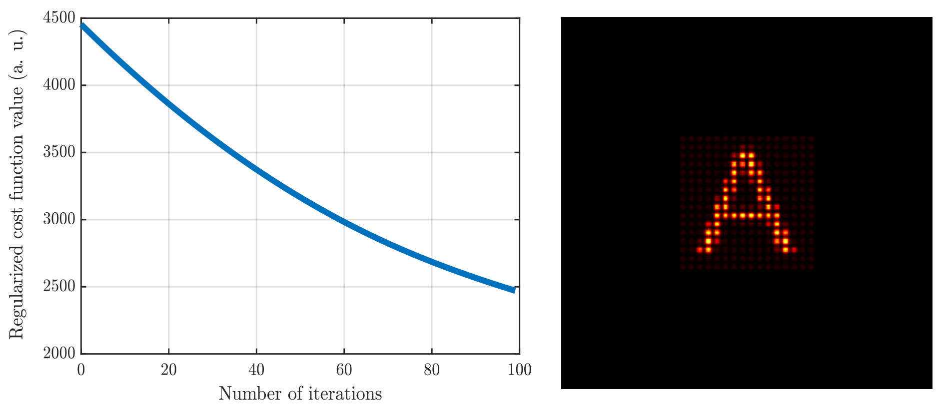


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Figure 4. (a) Regularized cost function after 100 iterations. (b) reconstruction image by the 16 × 16 few pixel SLM device.

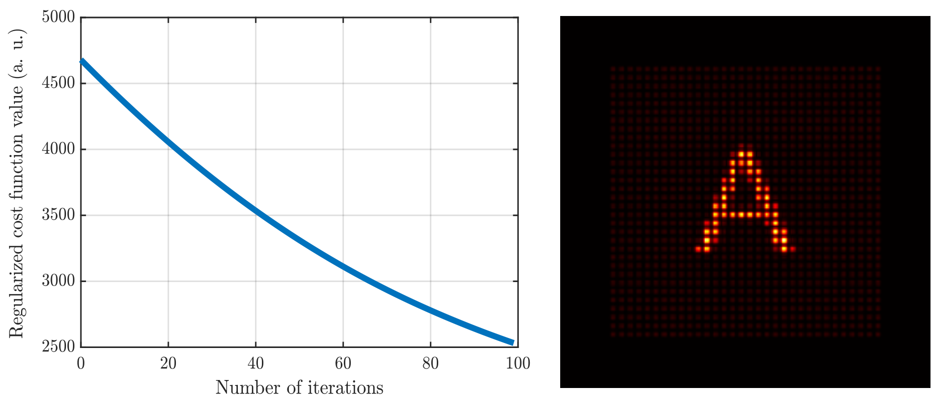

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Figure 5. (a) Regularized cost function after 100 iterations. (b) reconstruction image by the 32 × 32 few pixel SLM device.

4. CONCLUSIONS

We developed a CGH design algorithm that can generate an arbitrary illumination pattern using a few pixel SLM for holographic neural illumination. The proposed algorithm accounts for the constraints imposed by the small number of pixels by means of a regularized cost function. The effectiveness of the algorithm was demonstrated for the extreme case of 64 pixels. The use of the proposed algorithm enables the use of small footprint few pixel SLM, thus favoring miniaturization of *in vivo* optogenetic systems.

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