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Optimized random phase only holograms

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We propose a simple and efficient technique capable of generating Fourier phase only holograms with a reconstruction quality similar to the results obtained with the Gerchberg–Saxton (G-S) algorithm. Our proposal is to use the traditional G-S algorithm to optimize a random phase pattern for the resolution, pixel size, and target size of the general optical system without any specific amplitude data. This produces an optimized random phase (ORAP), which is used for fast generation of phase only holograms of arbitrary amplitude targets. This ORAP needs to be generated only once for a given optical system, avoiding the need for costly iterative algorithms for each new target. We show numerical and experimental results confirming the validity of the proposal.

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The capability of shaping light fields at-will is of great interest for many fields of research, like holographic displays [1,2], visual aberration correction [3], photogenetics [4,5], optical tweezers, and trapping [6], among others.

The most common schemes used for this purpose consist in the use of coherent illumination and phase only liquid crystal on silicon (LCOS) spatial light modulators (SLM) [7]. These devices can alter the phase of incident light depending on the pattern projected on them. The generation of the phase patterns needed to produce the desired change in light field for a given application is an open problem, where many different approaches have been proposed. Most of these approaches rely on iterative algorithms [8,9], which can be computationally demanding, thus making difficult the real-time manipulation of light fields using the current SLMs. Another issue is that these algorithms produce, at best, an approximation of the desired optical field. This means that the reconstructed field from the phase only hologram will present degradation, usually in the form of speckle noise [9].

When we are only interested in the reproduction of a given intensity distribution, as, for example, in holographic displays and holographic projectors [10], a fast solution can be found by multiplying the target intensity with a random phase mask. The phase of the Fourier transform (FT) of this product contains enough information about the target intensity to reconstruct a rough approximation. This effect was observed since the early stages of holographic techniques, when it was demonstrated that the phase of the light coming from highly diffuse objects was enough to ensure reconstruction [11].

The main advantage of this method, when compared with iterative algorithms like the Gerchberg–Saxton (G-S), is that a single random phase mask can be used for many intensity targets. Besides, each phase only hologram is generated with only three operations, namely, a multiplication of the intensity target with the random phase mask, a FT, and a phase extraction from the resulting FT.

However, as mentioned above, this method produces only a rough approximation of the target intensity. The degradation due to the loss of the amplitude information in the hologram plane is increased when using SLMs, which have a large pixel size and very limited resolution compared with other traditional mediums like holographic films. This makes the use of random phase masks for generation of phase only holograms a method of limited usefulness, despite its advantage in speed.

In this Letter, we propose a simple and straightforward technique to generate an optimized phase mask, which when applied to the generation of Fourier phase only holograms, show greatly improved performance over a normal random phase mask with quality close to the results obtained with the G-S algorithm.

Our proposal is to use the traditional G-S algorithm to optimize a random phase pattern for the resolution, pixel size, and target size of the optical system. This produces an optimized random phase (ORAP). Once an ORAP is generated for a given optical system, it can be used to generate large amounts of phase only holograms of arbitrary targets with a vast reduction in computation time over the G-S algorithm.

We first create a window corresponding to the support size of the target whose phase only hologram we want to generate. A random phase mask multiplies this window. We perform the inverse FT(IFT) of this product, and then follow several iterations of the standard G-S algorithm loop.

In these loops, we alternate between the SLM plane and the reconstruction plane. In each projection, the resulting amplitude is replaced with the target amplitude corresponding to each plane. In the case of the SLM target, we use a uniform amplitude with the same size as the SLM area, and, in the reconstruction plane, we use the previously created target window. A number of 20 iterations was enough to guarantee, in our simulations, an adequate approximation between the reconstructed window amplitude and the target window amplitude.

Once these iterations are completed, we take the ORAP, which is the phase of the reconstructed target window. The amplitude target whose phase only hologram we wish to generate then multiplies this ORAP. We perform the IFT of this product, and the amplitude of the result is set as a constant. This is our desired phase only hologram. After a FT, we can reconstruct the desired target. The entire process can be seen in the flow chart of Fig. 1.

Once an ORAP is obtained for a given optical system, it can be used for arbitrary amplitude targets with the same support size as the target window. If we wish to change either the size of the target, whose hologram we want to generate, or the optical system, a new ORAP must be generated.

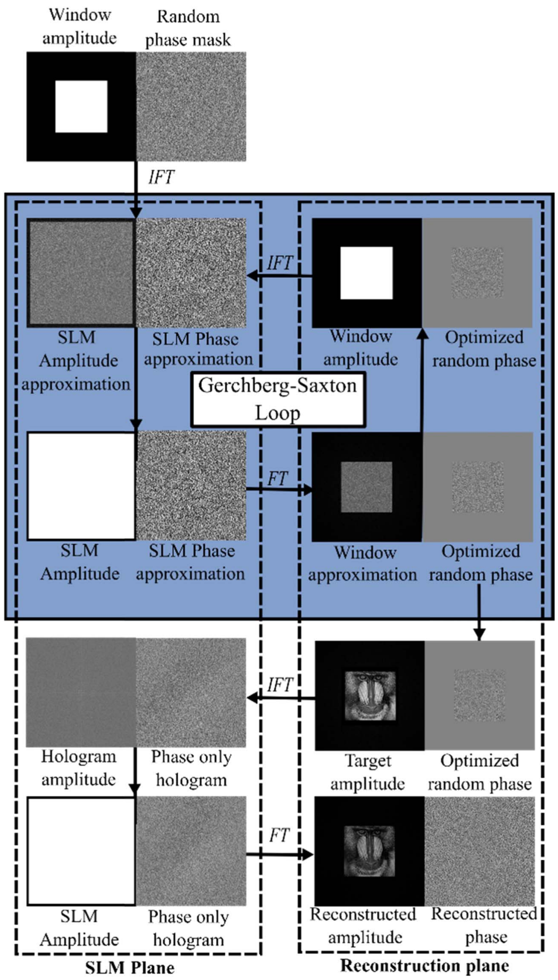

Fig. 1. Flowchart of the optimized random phase only hologram generation technique.

We now proceed to numerically test our proposal. First, we simulated the reconstruction of a single target with an ORAP optimized with an increasing number of iterations. The simulated SLM resolution was 1080 × 1080 pixels, while the target window and the target had a resolution of 1000 × 1000 pixels.

For each reconstruction, we calculated both the correlation coefficient (CC) and the peak signal to noise ratio (PSNR) between the target amplitude and the reconstructed amplitude, given by

$$\mathrm{PSNR} = 20\log_{10}\left[\frac{N \times M \times (2^B - 1)}{\sum_m\sum_n (I_o[n,m] - I_R[n,m])^2}\right], \quad (1)$$

and

$$\mathrm{CC} = \frac{\sum_m\sum_n (I_o[n,m] - \overline{I_o})(I_R[n,m] - \overline{I_R})}{\sqrt{(\sum_m\sum_n (I_R[n,m] - \overline{I_R})^2)(\sum_m\sum_n (I_o[n,m] - \overline{I_o})^2)}}, \quad (2)$$

where I_R is the reconstructed target, I_o is the original target, $\overline{I_R}$ and $\overline{I_o}$ are its mean values, $M \times N$ is the target resolution, B is the bit-depth of the target (8 bits in our simulation), and $[n, m]$ are pixel coordinates.

In Fig. 2, we show how the reconstruction improves as we increase the number of iterations used to generate the ORAP. The insets, corresponding to the eye of the reconstructed target images and the target, support the curve behavior. We now compare our proposal with the previous techniques, like G-S and random phase mask. To do this, we generated phase only holograms of the same amplitude only target directly using the G-S algorithm with a random phase mask and with an ORAP. Both the G-S result and the ORAP were obtained after 20 iterations.

In Fig. 3, we show the simulated reconstruction results by using the G-S [Fig. 3(b)], a random phase mask [Fig. 3(c)], and with an ORAP [Fig. 3(d)]. The target amplitude is shown in Fig. 3(a). As we can appreciate in the zoomed insets, the result from the random phase mask presents increased noise over the result with the ORAP. On the other hand, the result from the ORAP is comparable with the G-S result. These observations are backed up by the quality metrics shown in the figure.

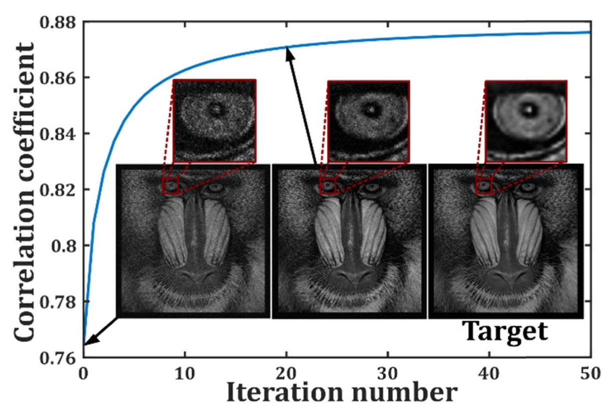

Fig. 2. Correlation coefficient between the target amplitude and the reconstructed amplitude from a phase only hologram generated with ORAP after increasing the number of iterations.

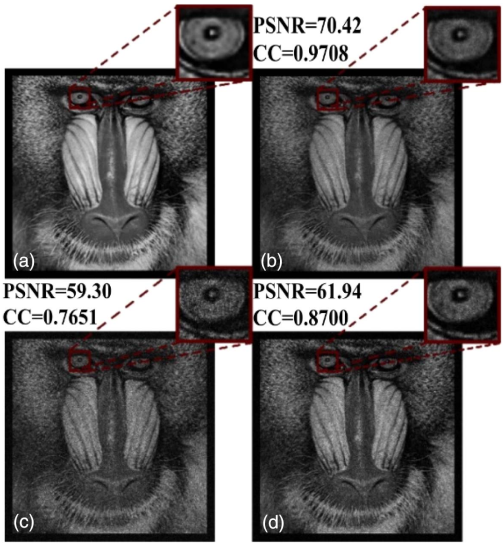

Fig. 3. Intensity pattern reconstructed from phase only holograms. (a) Target intensity, (b) reconstruction from phase hologram generated using the G-S algorithm, (c) reconstruction from the phase generated with a random phase mask, and (d) reconstruction from the phase generated using an ORAP.

The main advantage of the proposed technique becomes evident when there is a need to generate several holograms. To demonstrate this capability, we used the ORAP obtained to generate the reconstruction of Fig. 3(d) to generate the phase only holograms of three amplitude targets. The resulting reconstruction is shown in Fig. 4.

As we can see in Fig. 4, the reconstructed targets from the three holograms generated with the same ORAP are optimal.

Figure 5 shows that the performance of the ORAP does not vary significantly when applied to different amplitude targets. In particular, binary targets with relatively low spatial frequencies (like the zebra of Fig. 4) may show a slightly better reconstruction quality, however, this is also true when applying the traditional G-S algorithm.

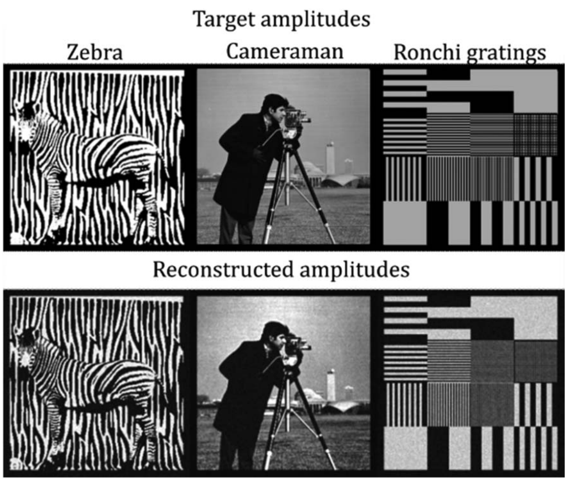

Fig. 4. Reconstruction of different target amplitudes from holograms generated using the same optimized random phase.

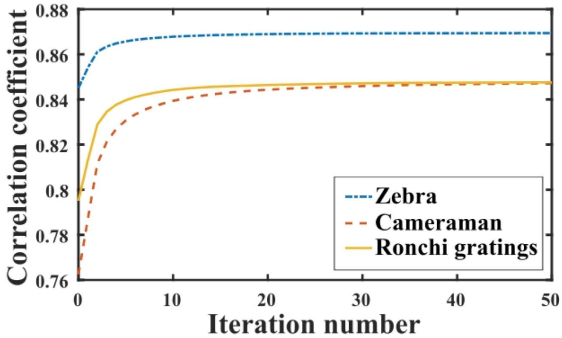

Fig. 5. Correlation coefficient between the targets of Fig. 4 and the reconstructed amplitude from a phase only hologram generated with the same ORAP after increasing the number of iterations.

Table 1 shows the computation time needed to generate the phase only holograms of the targets shown in Figs. 3 and 4. The generation of the phase only holograms for the four targets by directly applying the G-S algorithm took a total time of 2.384 s. For the same targets with the ORAP, it takes only 0.745 s. It is worth noting that of those 0.745 s, 0.521 were used in the generation of the ORAP. Once the ORAP is generated, each hologram takes approximately 0.056 s, instead of the 0.596 s necessary when directly applying the G-S algorithm. As the number of holograms that must be generated increases, the total computation time achieved with the ORAP becomes significantly lower than using the direct G-S algorithm. For all the numerical results reported in this Letter, a Ryzen 1700 processor with a NVIDIA GTX 1060 graphics processing unit (GPU) was used. All programs were written in MATLAB.

The previous result show that our proposal leads to remarkable increases in speed when large amounts of phase only holograms with the same target window must be generated.

To further validate the use of ORAP for phase only hologram generation, we also tested their experimental reconstruction. The reconstruction scheme is shown in Fig. 6.

A HOLOEYE PLUTO LCOS-SLM with 1920×1080 pixels resolution and a pixel size of 8 μm was used to display the phase only holograms. The target window for ORAP generation was 500×500 pixels with the same pixel size as the SLM. We used a diode-pumped solid-state (DPSS) laser with 532 nm wavelength and 50 mW of power as light source. The reconstruction FT was achieved with a lens of 150 mm focal length. The reconstruction images of the targets were taken with an Edmund Optics EO-12001C complementary

Table 1. Computation Time for the Generation of Phase Only Holograms of the Targets of Fig. 3 (Mandrill) and Fig. 4 (Zebra, Cameraman, and Ronchi Gratings) by Using an ORAP and by Directly Applying the G-S Algorithm

Process	ORAP (*s*)	G-S (*s*)
ORAP generation	0.521	–
Mandrill hologram	0.056	0.596
Zebra hologram	0.056	0.596
Cameraman hologram	0.056	0.596
Ronchi gratings hologram	0.056	0.596
Total time	0.745	2.384

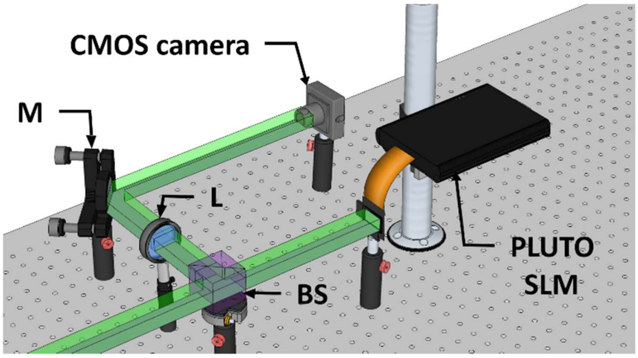

Fig. 6. Experimental setup for phase only holograms reconstruction (BS, beam splitter; L, lens; M, mirror).

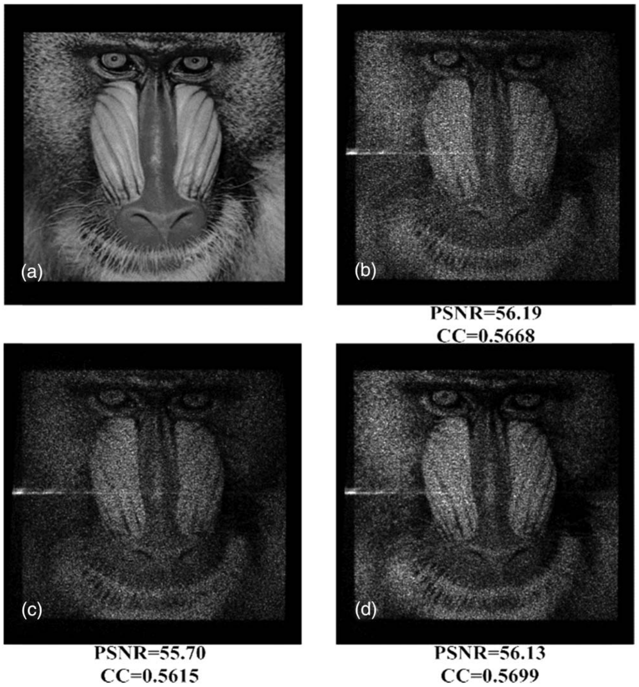

Fig. 7. Experimental reconstruction of phase only holograms. (a) Input target, (b) G-S algorithm, (c) random phase, and (d) ORAP.

metal–oxide–semiconductor (CMOS) camera with 3840 × 2740 pixels resolution and 1.67 μm pixel size. To avoid the undiffracted light of the SLM, all phase only holograms were multiplied by a phase grating [12].

The experimental reconstructions shown in Fig. 7 exhibit a similar behavior when compared to the simulated results. While all three methods present similar performance under the measured metrics, the random phase [Fig. 7(c)] is the worst for both CC and PSNR. On the other side, the ORAP and G-S hologram reconstruction present a very similar performance. We highlight that the chosen target exhibits a broad gray scale and a wide range of spatial frequencies.

The simulations and the experimental results presented in this Letter demonstrate the effectiveness of the ORAP method for fast generation of phase only holograms of arbitrary amplitude targets. This method may be of special interest for the generation of holographic movies or dynamic real-time light field manipulation, since, once the ORAP is generated, the holograms of all frames can be quickly produced with minimal computational cost without a need for further iterative procedures. For example, if we want to generate a time averaged holographic movie, we can pre-calculate ten ORAPs and use these ORAPs for each movie frame instead of having to apply the G-S algorithm for each frame ten times. In this scenario, the computation time advantage of the ORAP approach becomes considerably larger. This capability can also be used to dynamically target neurons for photostimulation, for real-time atom manipulation by means of light traps, and for fast adaptive optics aberration correction. Additional work is necessary to extend this approach to the generation of phase only holograms of three-dimensional (3D) targets. Some perspectives include exploring other iterative algorithms traditionally used for obtaining phase only holograms and their capabilities for random phase mask optimization.

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