Influence of the limited contrast of SLMs over the storage capacity of dynamic holograms

Yann Frauel, Gilles Pauliat, Gérald Roosen
Institut d'Optique, Unité de Recherche Associée 14 au Centre National de Recherche Scientifique, Centre Scientifique, Bâtiment 503, B.P.147, 91403 Orsay Cedex, France

Abstract

SLMs' finite contrast causes noise which bounds the number of storable holograms. We present a method to reduce this noise and increase the storage capacity.

Introduction

Holograms are widely used to store data or interconnect patterns to implement optical memories or neural networks [1]. Volume holograms, such as those recorded in photorefractive materials, can only be recorded optically by means of light modulators such as liquid crystal spatial light modulators [2], SLMs. In spite of the recent improvements of the characteristics of these SLMs, their finite contrast imposes some severe limitations on the information capacity of the stored holograms [3]. Indeed, during the recording, some light passes through the pixels that one would like to be ideally switched off. These undesired beams record parasitic holograms which are responsible for optical noise during hologram readout (i.e. data retrieval or use of the interconnections). The strength of these parasitic gratings can be computed if the recording sequence (i.e. set of images of data or interconnection patterns) is known.

Hereafter, we present how we compute the grating strengths at the end of the learning stage. We will then apply these results to some concrete cases in order to determine the effect of the limited contrast of the SLMs and then to estimate the storage capacity of these systems. At the end, we propose a method to decrease the influence of the parasitic gratings and thus to increase the system capacity.

Computation of the gratings after the recording stage

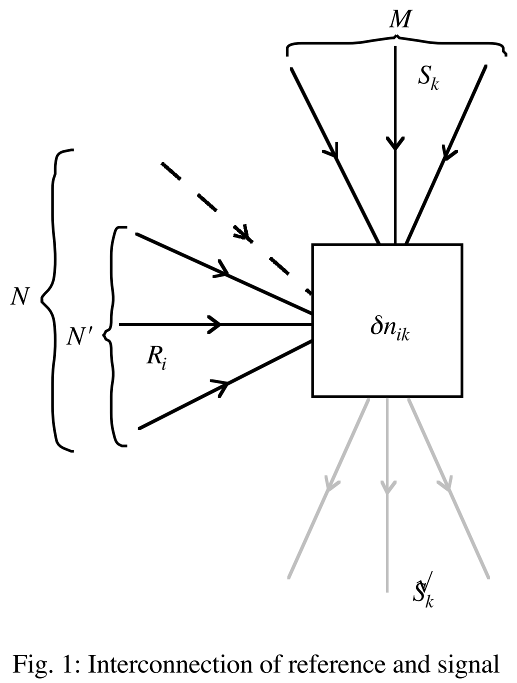

Fig. 1: Interconnection of reference and signal beams inside a holographic material.

Let N reference beams (with complex amplitudes R_i) be interconnected with M signal beams (with complex amplitudes S_k) inside a dynamic holographic material (Fig. 1). R_i interferes with S_k to create a grating whose index modulation is noted δn_{ik}. When the signal beams are removed, the reference beams are diffracted onto these gratings and generate M beams in the directions of the transmitted signal beams. We assume that the optical system is arranged so that a reference beam can only reconstruct the gratings it has recorded. This can be achieved by taking use of the angular Bragg selectivity. If the beams add coherently onto the detectors [3], their complex amplitudes are given by :

$$\tilde{S}_k = \frac{\pi d}{\lambda} \sum_{i=1}^{N} \delta n_{ik} R_i \quad , \ 1 \le k \le M \tag{1}$$

with d the thickness of the material and λ the optical wavelength.

The recording stage is an iterative process: at each step, a set of signal beams (the signal image) is presented simultaneously with a corresponding set of reference beams (the reference image). The gratings inside the material are then updated according to the law:

$$\delta n_{ik}^{(n+1)} = \frac{2 R_i^* S_k}{I_{ik}} \delta n_{\max} \left(1 - e^{-\frac{\Delta t}{\tau_0} I_{ik}} \right) + \delta n_{ik}^{(n)} \, e^{-\frac{\Delta t}{\tau_0} I_{ik}} \tag{2}$$

where $\delta n_{\max}$ is the maximum index modulation, I_{ik} the total intensity illuminating the grating, Δt the exposure time and τ_0 the writing time constant of the material for a unitary illumination. This formula is applicable to several kinds of dynamic holograms, including photorefractive crystals.

If the exposure time is short enough compared with the time constant and provided that the phase of each beam remains stable through the whole experiment, it can be shown that the modulations at the end of the recording process are expressed by:

$$\delta n_{ik} = 2\delta n_{\max} \frac{\langle R_i S_k \rangle}{\langle I_{ik} \rangle} \qquad (3)$$

where $\langle \ \rangle$ stands for the statistical mean. So, if one knows every reference/signal image couple, one can easily find the grating strengths once the recording stage is achieved. The responses (i.e. the diffracted amplitudes) to any new reference image can then be computed according to equation (1). The squares of these responses can be measured with a camera.

In each of the following examples we assume that we use two amplitude SLMs (one for the reference image and one for the signal image) with finite contrasts. We only want here to show the limitations caused by these contrasts, so we only study one simple configuration : during recording, only one reference beam and one signal beam are "on" at each iteration. Every "on" beam has the same intensity. Moreover we suppose that the reference beams are spatially multiplexed whereas the signal beams are angularly multiplexed (the opposite situation or angular multiplexing on both arms, would not change much to the conclusions as it would only modify the term $\langle I_{ik} \rangle$ in eq. (3)). Because of the limited contrast of the SLMs, pixels that should be "off" transmit a small amount of light which creates parasitic gratings. At the end of the learning process, a reference image with *N*' beams "on" among *N* is presented and we compute the resulting diffracted intensity. *N*'=1 corresponds to a holographic memory of data since each reference beam allows to read one stored image. On the other hand, *N*'>1 may correspond to a neural network. An analytic calculation of the index modulations and responses can be made for a few simplified cases [3].

Uniform contrast over the SLM

One of these simple cases is when we have two identical SLMs with the same contrast for all pixels that is to say for all beams. This particular example is fully deterministic and analytic formulae can be obtained [3]. This result can be reobtained with the approach we developed in the former paragraph.

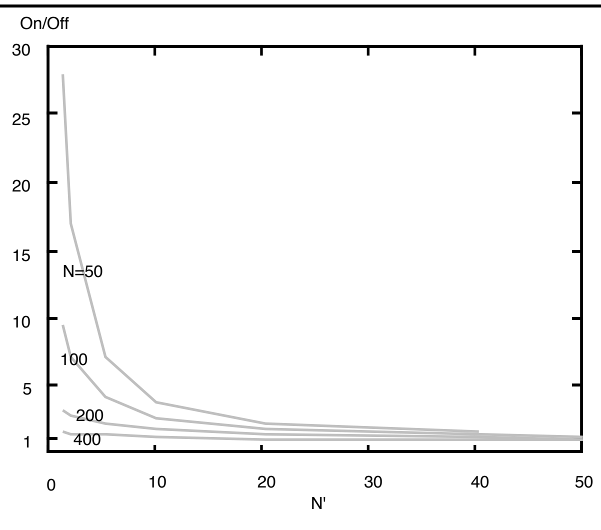

Fig. 2: Ratio between "On" and "Off" intensities vs *N* and *N*'

Because there is theoretically no dispersion between the "on" or the "off" beams, we consider the ratio between the intensities of these two kinds of beams. Fig. 2 shows the evolution of this ratio versus *N* and *N*'. In this example we take the intensity contrast of the SLMs equal to 1500:1. We notice that the ratio decreases rapidly when *N* and *N*' grow. Different sorts of noises that are likely to happen in a real set-up will prevent separation between these two categories when the ratio is low (typically less than 2), therefore the number of beams in this example would practically be limited to about one hundred. Nevertheless, as shown below, true SLMs present a non uniform distribution of the contrast which more severely limits the system capacity.

Contrast depending on the beam

Let us now consider another case where the contrast varies through the beams but remains constant for a given beam for the whole experiment. Once again we consider a pure amplitude noise. This could typically result from the fluctuations in the alignment of the ferroelectric liquid crystal SLMs. More precisely, if we assume that the "on" intensity of a beam is 1, we choose its "off" intensity randomly with a normal distribution probability, a mean of 0 and a standard deviation of 1/1500.

Fig. 3 shows the histograms of the responses (that is the number of "on" and "off" beams that provide a given intensity) for the same defects and the same learning (i.e. the same gratings) but for two different reference images. Here M=N=80 and N'=16. It can be seen that, even with this low number of beams, it becomes difficult to separate "on" beams from "off" beams due to the large dispersion of the responses. Moreover, the result strongly depends on the presented image. So this single example shows that we are in practice very limited by this problem of contrast.

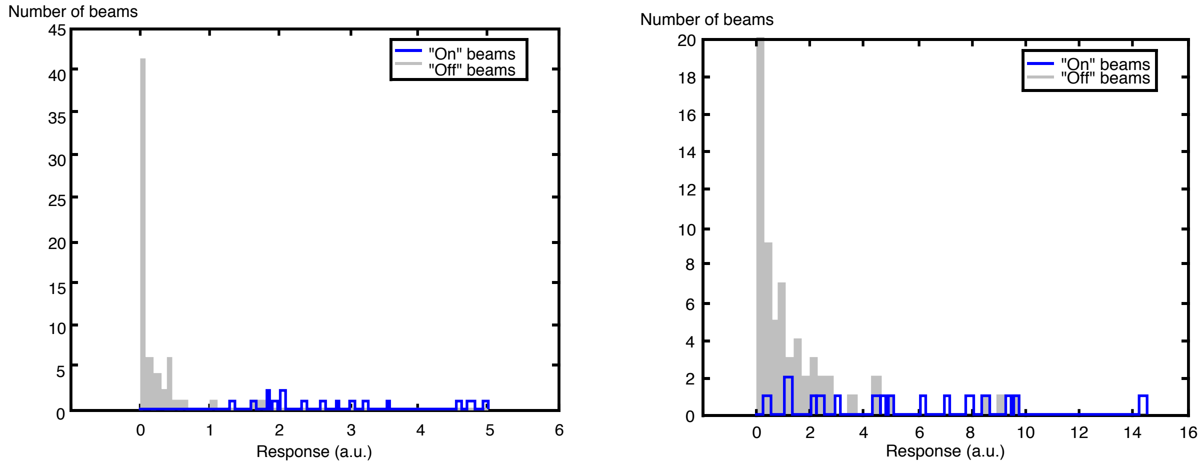

Fig. 3: Two examples of intensity histograms when contrast depends on the beam (N=80, N'=16)

Erasure of parasitic gratings with opposite image

The problem of dispersion of the responses that we encountered above is due to the parasitic gratings which are all different from each other. One possible solution to this problem can be to erase these gratings or at least to minimize them. In order to do so, we modify the learning process as follows: at each iteration, after presenting simultaneously the signal and the reference images, we keep the latter, switch off all the signal beams and turn their amplitudes into their opposites thanks to a π phase shifting modulator. The opposites of most of the previously stored parasitic gratings are thus recorded whereas useful gratings are not changed a lot (because of the difference of energy between "on" and "off" beams). This results in a cancellation of these parasitic gratings. We define the following signal to noise ratio (SNR) as a criterion:

$$r = \frac{\langle I_{on} \rangle - \langle I_{off} \rangle}{\sqrt{\sigma^2_{I_{on}} + \sigma^2_{I_{off}}}} \qquad (4)$$

where I_{on} and I_{off} stand respectively for the intensities of the "on" and "off" beams and σ is the standard deviation. For a good separation, r should be larger than 2.

Fig. 4 shows the results of this method for the same random contrast as in the former paragraph and for various values of N and N'. The curves represent the means of r over 20 trials. The SNR is roughly constant when N' grows but decreases when N grows. However, this approach allows to use many more beams than without the opposite image. As an example, the histogram of the intensity outputs for N=5000 and N'=1000 is drawn in fig. 5. Here, r equals 7.8 and the two groups of responses are well separated. The expected capacities make this approach very attractive for neural networks.

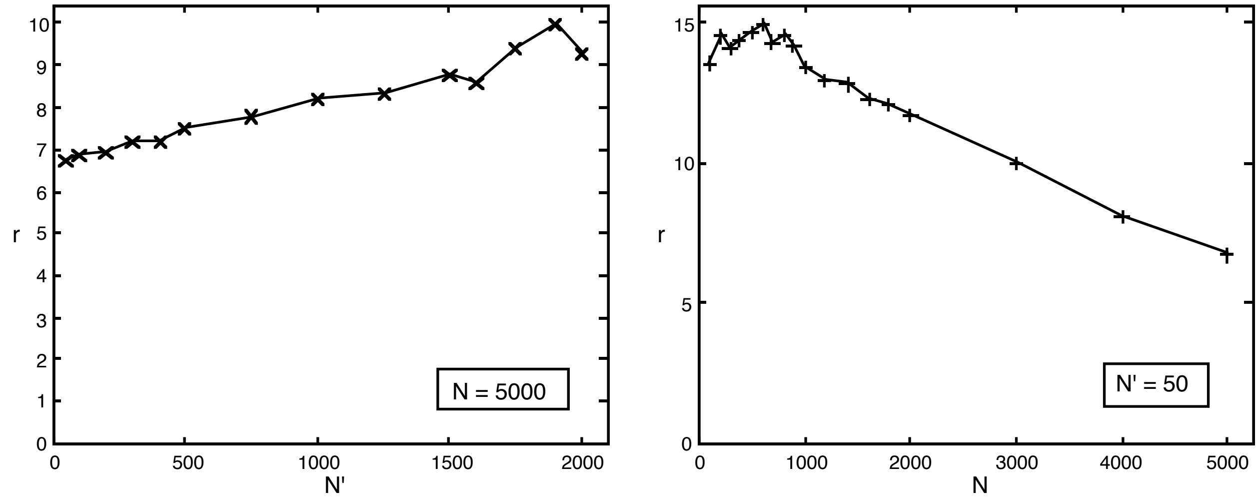

Fig. 4: Signal to noise ratio vs *N* and *N*' when presenting opposite image.

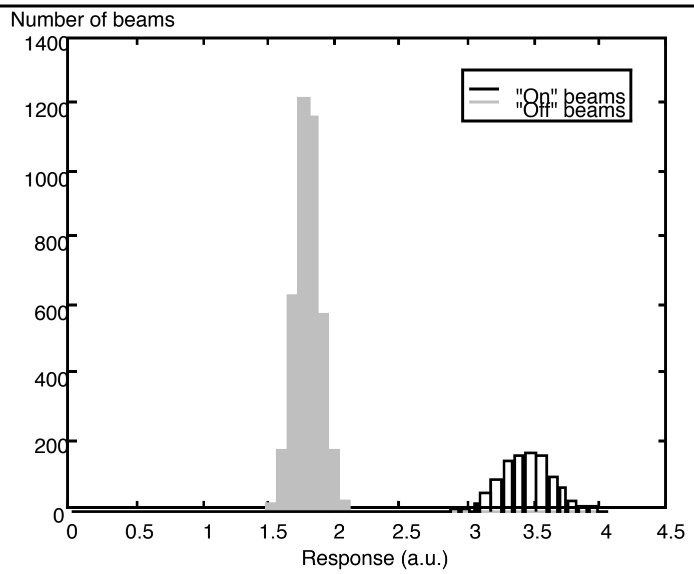

Fig. 5: Intensity histogram when presenting opposite image (*N*=5000, *N*'=1000)

Conclusion

We presented a method to easily compute the responses of a holographic interconnection system. We have shown that, because of the limited contrast of available SLMs, the expected capacities with the usual recording procedures are very low and make these systems of very modest interest. We presented a technique to overcome this limitation by presenting, during the learning, the opposite of each signal image. The dispersion of the responses is then greatly reduced which allows to use many more beams.

References

[1] Y. Qiao, D. Psaltis, Appl. Opt. 31 (1992) 3285-3288.

[2] J. L. de Bougrenet de la Tocnaye, L. Dupont, Appl. Opt. 36 (1997) 1730-1741.
[3] Ph. Aing, G. Pauliat, G. Roosen, Opt. Comm. 143 (1997) 87-94.
[4] C. Soutar, S. E. Monroe, J. Knopp, Opt. Eng. 33 (1994) 1061-1068.