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Dynamic greyscale intensity landscapes: generalized phase contrast and computer-generated holography

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Summary

Generalized phase contrast and computer generated phase holography have been demonstrated to be viable technologies for generating greyscale intensity landscapes. As phase modulation technologies, they offer minimal absorption losses and optimal efficiency. Adopting information capacity as a general framework, we examine and compare the merits of these two techniques. We tackle metrics such as space-bandwidth product, output display resolution, efficiency, speckle noise, computational load and device requirements. The analysis takes into account the perspective of potential end-users.

Introduction

Dynamic greyscale intensity landscapes can enable spatially controlled light-matter interaction with potential applications in materials processing [1], microscopy [2], non-contact optical manipulation at microscopic scales [3], among others. Amplitude modulation technologies, while offering high image fidelity, suffer from energy loss. Phase modulation techniques such as generalized phase contrast (GPC) [4] and computer-generated holography (CGH) [] are attractive for their lower energy loss, but can be subject to some performance tradeoffs.

We can expect that different performance metrics will be relevant to the different applications of but one can attempt at an overall comparison based on a general guiding principle. This work is one such attempt to benchmark the performance of GPC with respect to CGH for dynamic greyscale intensity landscapes. Ideas from information theory are used as a framework for our analysis.

Performance benchmarks

Generating dynamic greyscale intensity landscapes may be regarded as a communication system. A sender transmits two-dimensional information to a receiver through a communication channel consisting of computational and optical components as illustrated in Fig. 1.

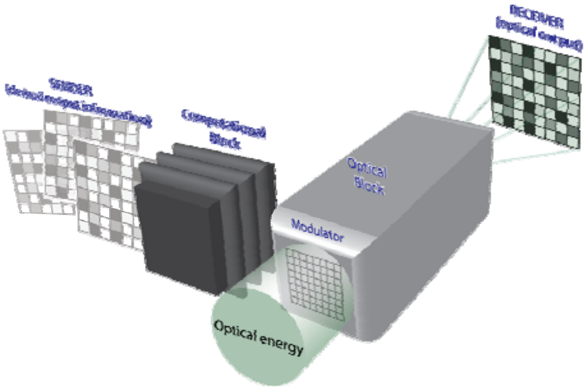

Fig 1. Dynamic grayscale intensity landscape generation as a communication system.

The information capacity of this communication channel is

$$N_C = \left(1 + L_t \Delta f_t\right)\left(1 + L_x \Delta f_x\right)\left(1 + L_y \Delta f_y\right)\log_2\left(1 + s/n\right), \tag{1}$$

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where the transmission is over a time interval L_t using a temporal bandwidth Δf_t. The output consists of a signal, *s*, with an additive noise, *n*, and is confined within a rectangular area bounded by $\{-0.5L_x \le x \le 0.5L_x$ and $-0.5L_y \le y \le 0.5L_y\}$. It also considers an effective band-limiting aperture that transmits spatial frequencies within $\{-0.5\Delta f_x \le f_x \le 0.5\Delta f_x$ and $-0.5\Delta f_y \le f_y \le 0.5\Delta f_y\}$.

The first term describes the temporal degrees of freedom. Using a direct phase-to-intensity-mapping, GPC has minimal computational overhead and allows for modulator-limited dynamic refresh rates. On the other hand, CGH involves global mapping where each output point requires optimization of the entire input field. This optimization can reduce the temporal bandwidth of the computational block when generating high fidelity outputs.

The next two terms describe the spatial degrees of freedom, or the number of uniquely addressable output points. The direct spatial mapping in GPC means the number of addressable output points matches that of the input modulator. For CGH, interference effects between adjacent output elements can generate speckled outputs. Techniques for avoiding speckles, such as addressing sufficiently separated points and allotting signal and noise windows reduce the number of independently controllable output points.

The last term describes the number of recognizable intensity greyscale levels based on the signal-to-noise ratio, which is related to the achievable energy efficiency. The GPC efficiency is fundamentally limited by the energy lost to the tail portion of the synthesized reference wave that extends beyond the relevant output region. Under optimized parameters, numerical simulations show that efficiencies exceeding 80% are achieved for smaller GPC filters, and asymptotically approach 100% for larger filters. For CGH, the efficiency is limited by the energy lost to spurious higher orders and the intensity roll-off due to the diffraction from each pixel in the input modulator. When addressing the widest available output region, CGH efficiency cannot exceed 52%. Achieving higher CGH efficiency is obtained by restricting the patterns close to the optical axis, which trades off and reduces the number of independently addressable output elements.

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