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Stratified Diffractive Optical Elements for Azimuthal Multiplexing

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Abstract: We design and demonstrate stratified diffractive optical elements to achieve azimuthal multiplexing, a technique that enables recording multiple outputs that are switched upon the rotation of one or more layers by a certain angle. © 2021 The Author(s)

1. Introduction

Diffractive optical elements (DOEs) offer novel paths to light manipulation [1], providing flexibility not available in conventional refractive/reflective optics. Further, the ever-increasing computer hardware capabilities and computational techniques enable DOEs to generate user-defined wavefronts from arbitrary coherent inputs, by virtue of the degrees of freedom that can be addressed individually and independently [2–6]. Mature and emerging applications include beam shaping [7], 3D display [8], information security [9], optical tweezers [10], novel microscopy [11], and optogenetics [12].

Multiplexing in 3D diffractive optics allows multiple pages of data to be encoded in the spatial or frequency domain. The independent information appears intertwined in the recording medium by means of the coding process, while the retrieval of an individual page with minimum crosstalk from others is the result of a decoding process. Here, we propose azimuthal multiplexing implemented with stratified DOEs. Azimuthal multiplexing enables recording of multiple output signals switched upon the rotation of one or more layers of the DOE with respect to the others, i.e. the information is encoded in the azimuthal dimension of the diffractive optics. Compared to the most common angular and frequency (wavelength) multiplexing, the azimuthal multiplexing system is compact while the numerical aperture (NA) is unaffected with multiplexing. The multiplexing design is implemented with iterative projection optimization algorithms with the so-called distribution on layers method. In the experiment, we fabricate the planar layers using photolithography, with the characterization showing good agreement with the design.

2. Design

We model the stratified DOEs with multiple 2D layers of phase modulation spatially separated by short distances in a uniform medium (Fig. 1a). Each layer can rotate with respect to a common axis at the center (the optical axis). We apply the forward propagating model from input to the wave field in front of the *k*-th layer. We then continue to the reconstruction plane where the amplitude is updated with the pre-defined reconstruction field and the phase is kept unchanged. Next, the backward propagation, described by the conjugation of the forward propagation, is applied from the reconstruction field to the wave field after the *k*-th layer. Thus, the phase modulation can simply be derived by dividing the two terms obtained above. We update the phase values and iterate until the algorithm reaches a satisfactory solution. This process is repeated for all the remaining layers.

In a second step, we rotate the *k*-th layer to an abitrary angle, and repeat the above process with another reconstruction field. As a result, we obtain the phase modulation optimized for the second target. We follow the same procedure until all the multiplex targets are encrypted in all the layers. To ensure all the multiplexing cases being considered are evenly distributed among all the layers, we apply a parallel projection, described by the following equation

$$\phi_{j,0} = \frac{1}{m}\sum_{i=0}^{m}\phi_{j,0}^{\theta i},\ j = 0,\ 1,\ \ldots,\ N, \tag{1}$$

where ϕ is the phase modulation function, θ is the rotation angle, m is the number of targets to be encoded, and N is the number of layers in the diffractive optics. All the calculations up to this point conclude one iteration in the optimization loop. The algorithm keeps iterating until the results are satisfactory or the iteration number is reached.

It should be noted that since the inverse design problem is ill-posed, the convergence of the algorithm is not always guaranteed. The feasibility depends on the task complexity (the number of functions to be multiplexed) and degrees of freedom available (the number of layers and number of pixels in each layer).

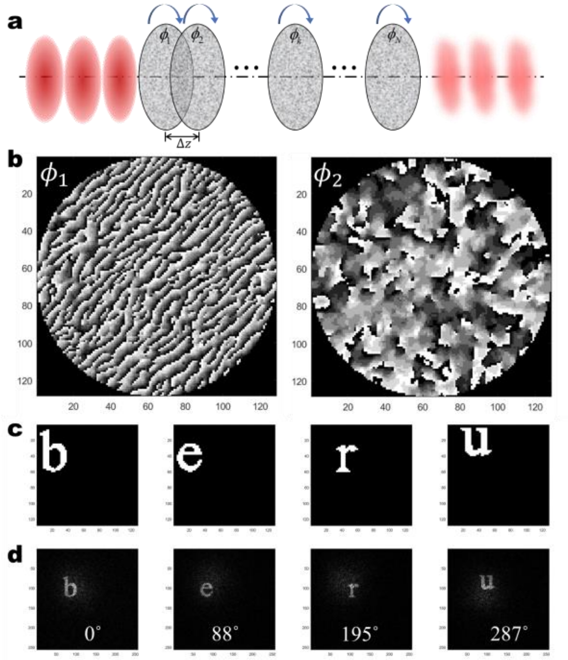

Fig. 1. (a) Physical model of stratified diffractive optical elements. (b) The design of two layers of phase modulation discretized to 8 levels. (c) Target images of the 4 letters to be multiplexed. (d) Numerical reconstructions from the stratified diffractive optical elements while the second layer is rotated at angles specified by design.

3. Results

To demonstrate the principle, we design a stratified diffractive optics with two layers. The pixel number in each layer is 128×128, with the pixel size of 40μm×40μm, and the layer separation is 1mm. The illumination wavelength is 633nm. For the targets, we choose 4 arbitrary patterns, i.e. the letters of “b”, “e”, “r”, “u” (Fig. 1c), encoded at 0˚, 88˚, 195˚, and 287˚ of the orientation of the second layer. Fig. 1b shows the phase modulations of the two layers using the design method. The numerical reconstruction results are shown in Fig. 1d. Experimentally, we implement the designed two layers using the photolithography method. The substrates are 1mm thick fused silica, with the 8-level phase pattern fabricated on the surface by a 3-step binary exposure photolithography method and subsequent RIE etching. After fabrication, the samples are mounted on multi-axis translation stage with rotation control, and they are facing each other such that the separation can be freely adjusted. The experimental results are in good agreement with the design target.

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4. References

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