Improved Spatially Dithered Beam Shapers Using Direct Binary Search

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Abstract: Direct binary search is used to optimize spatially dithered distributions of transparent and opaque pixels for beam shaping, improving the performance of spatial gain precompensation for laser systems, and wavefront metrology by optical differentiation.

OCIS codes: (140.3300) Laser beam shaping; (100.2810) Halftone image reproduction

1. Introduction

Beam shaping is an important technology for optical engineering. Beam shapers based on spatially dithered distributions of transparent and opaque pixels are used for spatial gain precompensation on large-scale laser facilities, wavefont sensing, and coronagraphy [1–3]. Their design relies on digital halftoning algorithms developed for rendition of gray-scale images by black and white pixels [4]. For high-performance algorithms such as error diffusion, the noise from pixelation and binarization is at high spatial frequencies that are not perceived by the human eye, or in the case of beam shapers, that are efficiently removed by a far-field aperture. An iterative algorithm that specifically pushes the noise out of the far-field aperture has greatly improved the beam-shaping quality while increasing the manufacturability tolerance [5].

We demonstrate the use of a full direct binary search (DBS) [6], where the pixel chosen at each iteration can either have its transmission state toggled or be swapped with one of its neighbors, for model-based design of binary pixelated beam shapers, showing significant improvement over previous work [5] for beam shaping and new results for the newly developed optical differentiation wavefront sensor (ODWS) [2].

2. Model-Based Design of Spatially Dithered Beam Shapers Using Direct Binary Search

The distribution of transparent or opaque pixels to approximate the spatially varying transmission $T(x,y)$ after far-filtering is iteratively optimized using the rms error ε between T and $|E'|^2$, where E' is the field of the input pixel distribution propagated in a $4f$ optical system with a far-field circular aperture [Fig. 1(a)]. A pixel is randomly chosen at iteration j, and ε is evaluated for a transmission-state toggle of that particular pixel ($\varepsilon_{\text{toggle}}$) and for up to the eight transpositions of the pixel with its neighbors ($\varepsilon_{\text{swap},k}$) [Fig. 1(b)]. To speed up error evaluation relative to propagating up to nine new pixel distributions to the far field [5] or to the image plane, the field resulting from propagating a single pixel is initially calculated so that the fields at the image plane and corresponding errors are calculated without Fourier transformation. The pixel distribution corresponding to the lowest error is chosen for iteration $j + 1$, and the process continues until the error stagnates.

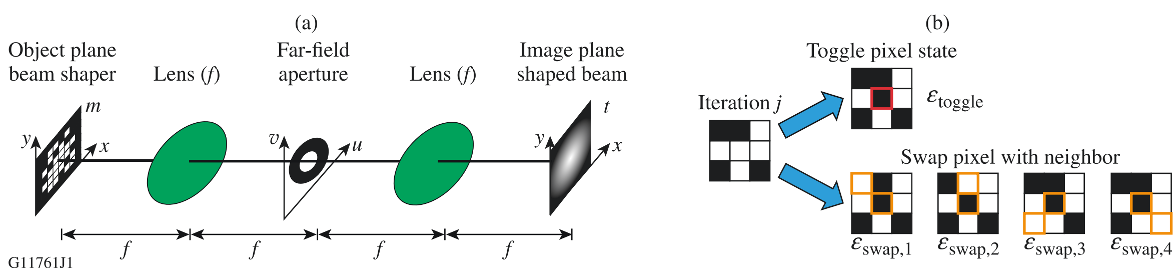

Fig. 1. (a) Example of beam-shaping architecture. (b) Mask detail around the pixel chosen at iteration j (at the center), showing the mask status after toggling its transmission state and after swapping it with its (four in this example) neighbors having a different transmission.

3. Application to Laser Beam Shapers

Application of the DBS to approximate the spatially varying transmission shown in Fig. 2(a) through a $4f$ optical system ($f = 1$ m, 4-mm-radius pinhole) with 10-μm pixels leads to a peak-to-valley error equal to 0.15% for an initial pixel distribution obtained with error diffusion after ~3 million iterations [Figs. 2(b) and 2(c)]. This is a large improvement over error diffusion without optimization (1.5% error) and over only toggling the transmission state without neighbor swap (0.4% error). Swapping pixels is generally the optimal decision compared to transmission-state toggling [Fig. 2(d)]. The performance of beam shapers obtained by applying the DBS to an initial distribution obtained with a random-draw algorithm [1], in particular their higher manufacturing tolerance, will be described.

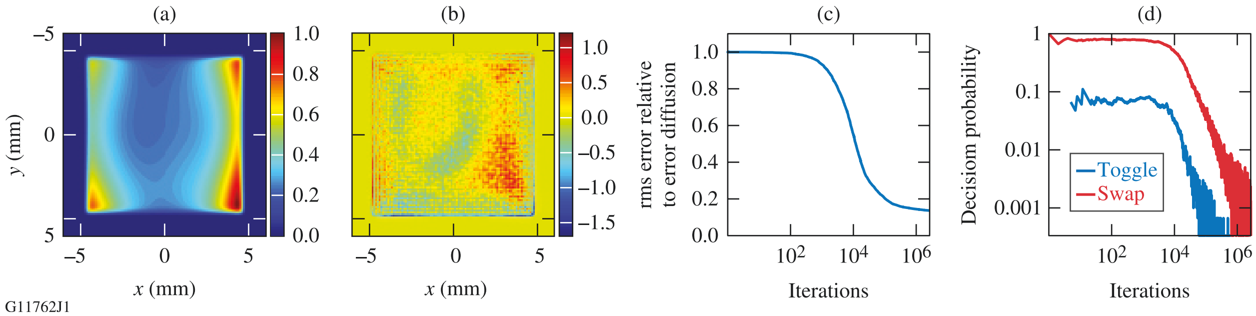

Fig. 2. (a) Target beam shape; (b) difference between fluence obtained at the image plane and target beam shape; (c) rms error ε scaled to the rms error obtained for a beam shaper calculated by error diffusion; (d) decision probability.

4. Application to the Optical Differentiation Wavefront Sensor

The ODWS uses a linear transmission gradient in the far field of the wave under test to measure a fluence distribution F_x from which the wavefront gradient along x is determined [Fig. 3(a)]. The wavefront is reconstructed from two gradients measured in two orthogonal directions. Binary pixelated filters are an excellent technological solution to the precise realization of a transmission gradient, with performance limited by detection-plane noise [2]. We apply the DBS to a linear transmission gradient varying from 0 to 1 over a 1-cm distance and an initial distribution of 10-μm pixels designed by error diffusion, then use the initial and optimized pixel distributions to simulate the ODWS performance. The rms reconstruction error for Zernike polynomials functions of the second, third, and fourth power of the radius defined over the 1-cm-diam input pupil of the wavefront sensor is lowered when using the filter optimized by DBS instead of the initial error-diffusion filter [Figs. 3(b) and 3(c)]. This improvement will be quantified as a function of pixel size and aperture size.

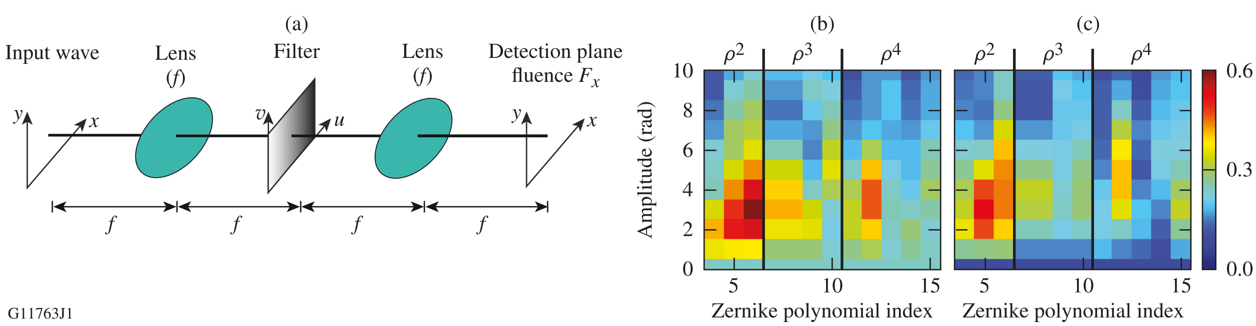

Fig. 3. (a) ODWS principle. [(b),(c)] rms error over the 1-cm aperture for Zernike polynomials in second, third, and fourth power of the radius (Noll index between 4 and 15) for a filter designed by error diffusion before and after optimization, respectively.

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