Supplementary Information for Single-Shot Quantitative Differential Phase Contrast Microscopy based on Support-Domain Constraint

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ABSTRACT

This document provides supplementary information for “Single-Shot Quantitative Differential Phase Contrast Microscopy based on Support-Domain Constraint” (SDC-DPC). We present more comparison simulations and to further demonstrate the robustness of SDC-DPC.

Contents

Supporting Information S1. Supplementary simulations on the robustness of SDC-DPC

To demonstrate the recovery capability of the SDC-DPC algorithm under low signal-to-noise ratio conditions, we evaluated the noise robustness of several representative phase transfer functions (PTFs). In the microlens array simulation experiment, Gaussian noise was introduced into the forward-simulated intensity maps to simulate practical imaging disturbances. The added Gaussian noise has a variance of 0.0000001. This parameter setting aims to compare the basic performance of different PTFs under noisy conditions, thereby examining the phase reconstruction algorithm's ability to suppress noise. This simulation is conducted under inverted microscope imaging conditions. The phase image acquisition size is set to 600×600 pixels, corresponding to a single pixel size of 0.294 μm. The system employs an imaging light source with a wavelength of 510 nm and is equipped with an objective lens featuring 10× magnification and a numerical aperture (NA) of 0.4 to align with common simulation scenarios for differential phase contrast imaging. In this simulation, forward-simulated intensity maps with Gaussian noise under four illumination patterns (uniform semi-circle, gradient semi-circle, gradient semi-ring, and uniform semi-ring) and one-step deconvolution results with different regularization parameters are simulated for detailed comparison, as shown in FIG. S1.

Under noiseless conditions, with the regularization parameter set to 0.000001, the reconstructed phase maps are relatively ideal. All four illumination patterns exhibit significant loss of lateral fringes, with their performances being similar to each other, as shown in FIG. S1(b). After introducing noise, under the same regularization parameter: the reconstruction results with semicircular illumination show noticeable speckle noise, making the originally missing fringes difficult to identify; the results with gradient semi-ring illumination have reduced noise, but the issues of missing fringes and structural blurring persist; uniform semi-ring illumination is least affected by noise, and its reconstruction results are closest to those under noiseless conditions, as illustrated in FIG. S1(c3). When the regularization parameter is increased to 0.001 (FIG. S1(c4)), the phase map corresponding to semicircular illumination darkens overall, and the shape of the microlens array is severely eroded and difficult to recognize. In contrast, the reconstruction results with annular illumination show only a slight decrease in brightness. By comprehensively comparing the deconvolution results of noisy intensity maps under different regularization parameters, it can be concluded that the PTF corresponding to uniform semi-ring illumination demonstrates the highest noise robustness and the greatest stability with respect to regularization parameter variations. This conclusion aligns with the calculation results of the optimized illumination metrics in the paper, thereby verifying that the proposed optimal single-shot illumination scheme exhibits stronger noise resistance and better robustness.

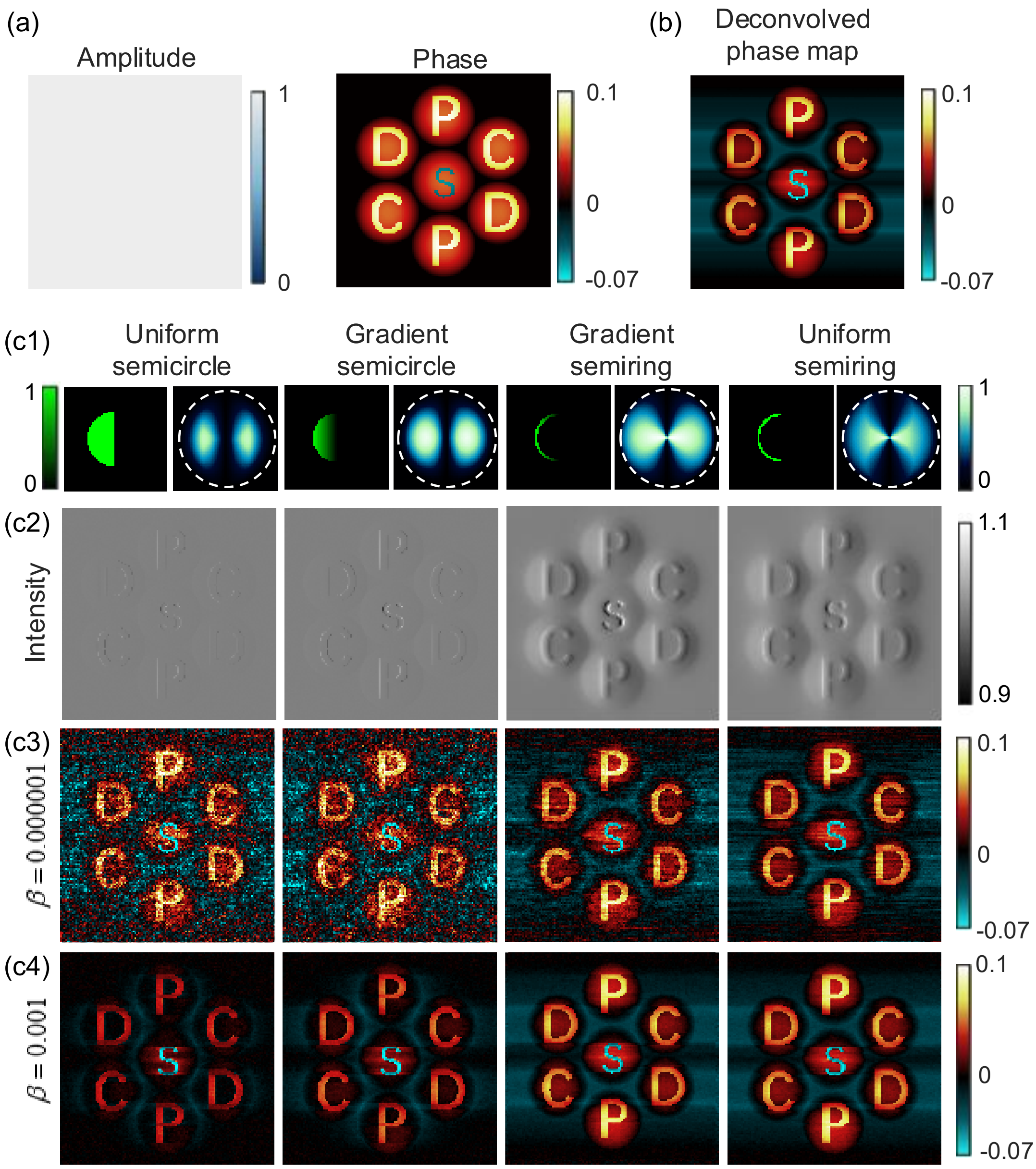

FIG. S1. Simulation results of phase transfer function robustness tests under four representative illumination patterns. (a) Amplitude and phase components of the simulated pure-phase object; (b) Phase maps obtained via one-step deconvolution of noise-free forward intensity maps; (c1) Simulated PTFs of the illumination patterns for uniform semi-circle, gradient semi-circle, gradient semi-ring, and uniform semi-ring modes; (c2) Forward-simulated intensity maps with Gaussian noise for the four illumination patterns; (c3) One-step deconvolution phase results with a regularization parameter of 0.000001 for the four illumination patterns; (c4) One-step deconvolution phase results with a regularization parameter of 0.001 for the four illumination patterns.

Next, using the left-half illumination intensity maps with simulated Gaussian noise under four illumination patterns as input for the SDC-DPC algorithm, 100 iterations were performed to compare their single-shot phase recovery results and support domain recovery results, as shown in Figs. S2(c)-(d). From Fig. S2(c), it can be observed that under uniform semi-ring illumination, the phase recovery result is nearly complete, with only a very small number of lateral fringes not fully restored compared to the ideal phase map; whereas under uniform semi-circle illumination, due to the introduction of Gaussian noise, significant phase gaps remain even after iteration, and the phase values are notably lower. As shown in Fig. S2(d), blue arrows indicate the region of difference between the reconstructed support domain and the ideal support domain. The support domain under semi-circle illumination exhibits an inward-shrinking boundary with a jagged and non-smooth circular boundary; in contrast, the support domain under semi-ring illumination is closer to the ideal case, featuring a smooth and complete circular boundary with only minor errors in the background. These simulation results verify that the SDC-DPC algorithm is affected to some extent by noise in terms of both phase recovery and support domain recovery, and such errors increase with higher noise levels; however, under the optimal uniform semi-ring illumination condition, the algorithm demonstrates a certain level of noise resistance, ensuring the stability of the reconstructed phase map and the recovered support domain.

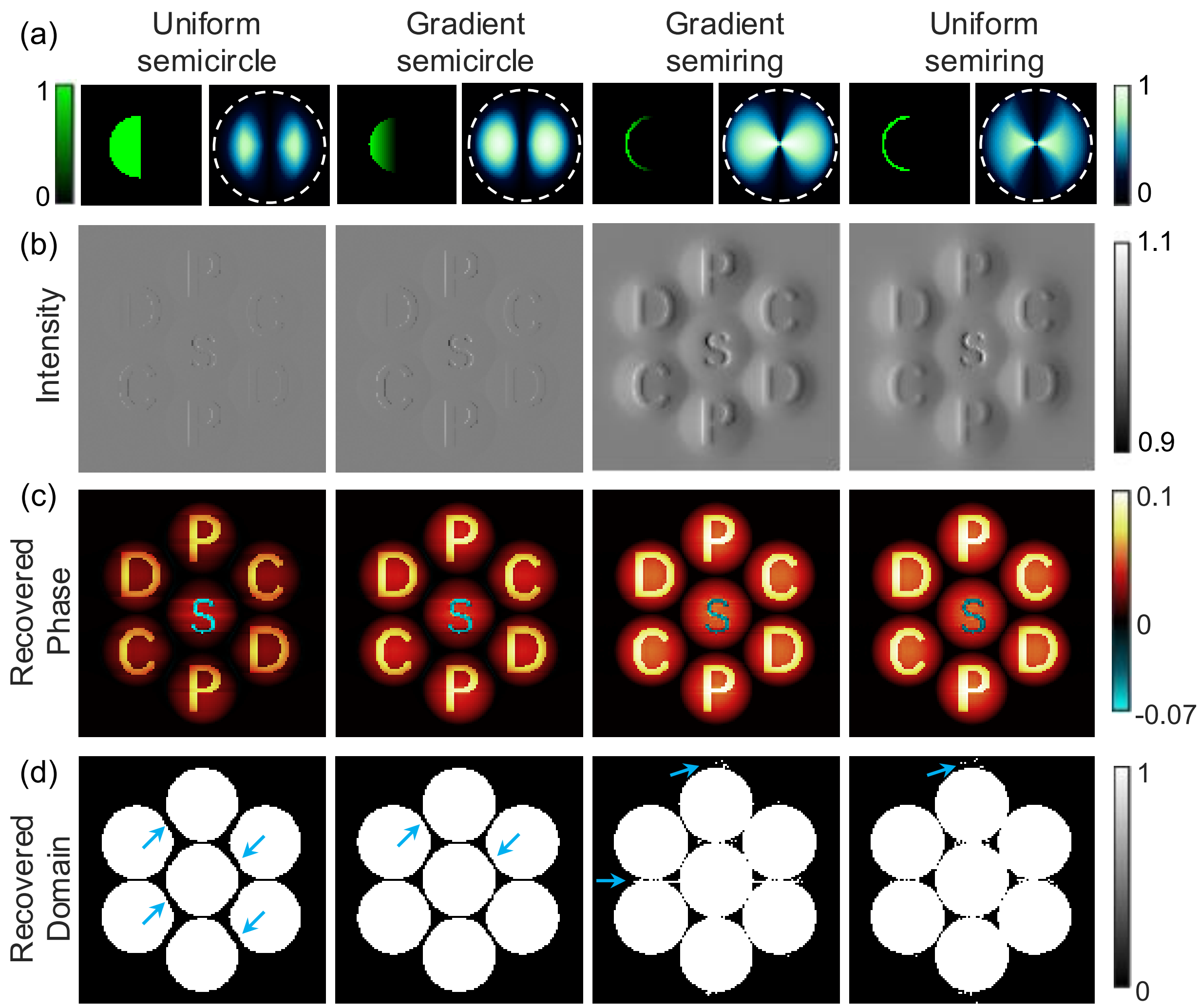

FIG. S2. Simulation results under four representative illumination patterns. (a) Simulated PTFs of the illumination patterns for uniform semi-circle, gradient semi-circle, gradient semi-ring, and uniform semi-ring modes; (b) Forward-simulated intensity maps with Gaussian noise for the four illumination patterns; (c) SDC-DPC phase reconstruction results after 100 iterations for the four illumination patterns; (d) Support domain recovery results after 100 iterations for the four illumination patterns.

Supporting Information S2. Supplementary code for SDC-DPC.

We provide the open-source code of SDC-DPC, which is available at Compressed file SDC-DPC.zip . In this section, we will introduce the configuration environment and the file structure of open source information, as well as the operation guide.

1. Configuration environment

The open-source code is developed on the MATLAB platform (version R2023a or later) and is conducted on a computer equipped with an Intel Core i5-12500H processor and 16 GB of RAM, without GPU acceleration. The minimum system requirements for running the code may be lower.

2. File structure

The raw input images should be placed in the input directory. The example files are currently in the .mat format and can be modified as needed.

- phase600_.mat: example input file.

3. Operation Steps

A. Place the ideal phase image into the project folder and read it in the code.

B. Open the SDC_DPC.m file in MATLAB and adjust the acquisition parameters according to the specific characteristics of the input data.

C. Run SDC_DPC.m. The code will automatically perform iterative reconstruction and display the final SDC-DPC phase retrieval result after 100 iterations.

D. To facilitate result visualization and detailed comparison, SDC_DPC.m automatically enables the display of the iterative process. While this increases the overall runtime, it clearly shows the updates and recovery of the support region, phase map, and corresponding Fourier spectrum during each iteration.