Resolution Enhancement in Digital Holography through Adaptive Speckle Illumination

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We demonstrate Speckle Illumination Digital Holography (SIDH), which improves lateral resolution by combining multiple decorrelated speckle illuminations. Experiments with a USAF test target confirm the resolution gains, although higher numerical illumination apertures reduce contrast.

1 Introduction

Digital Holography (DH) captures both amplitude and phase, enabling nanometer-scale resolution but is limited by its coherent nature, which restricts high spatial frequency transmission, resulting in lower lateral resolution compared to incoherent imaging [1, 2]. This work introduces Speckle Illumination Digital Holography (SIDH), using multiple decorrelated speckle illuminations to enhance lateral resolution in DH, demonstrated for reflective surface samples.

2 Optical Setup

The schematic optical setup is shown in Figure 1.

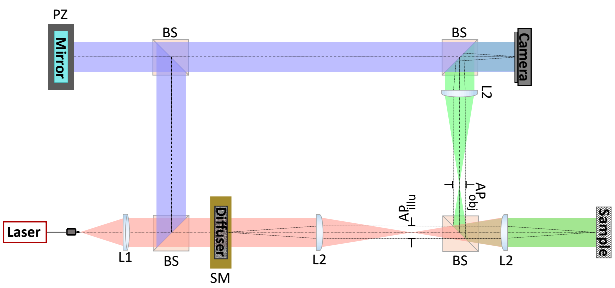

Fig. 1 *Schematic representation of the optical setup. L: Lens, BS: Beam splitter, SM: Stepper motor, AP: Aperture, PZ: Piezo actuator.*

A DBR laser diode (780 nm) is collimated and split into reference and object beams. The object beam passes through a holographic diffuser, creating a speckle pattern imaged 1:1 onto the sample via a 4f system. An aperture in the Fourier plane tunes the illumination numerical aperture $\mathrm{NA}_{\mathrm{illu}}$, controlling speckle size. Reflected light is imaged onto a camera (4112×3008 pixels, 3.45 µm pixel pitch) by another 4f system, with an aperture setting the object-side numerical aperture $\mathrm{NA}_{\mathrm{obj}}$. The reference beam interferes with the object beam at the camera using on-axis holography with four $\pi/2$ phase-shifted interferograms, achieved by a piezo-actuated mirror. The diffuser, moved by a stepper motor, generates uncorrelated speckle patterns by displacing at least the mean speckle size, $\delta_S = \lambda/\mathrm{NA}_{\mathrm{illu}}$. For calibration, the sample is replaced with a mirror at the same plane, and diffuser holograms are recorded using the same set of diffuser positions. To acquire holograms with plane-wave illumination, the diffuser is removed from the illumination path.

3 Process of SIDH

The procedure for SIDH is illustrated in Figure 2.

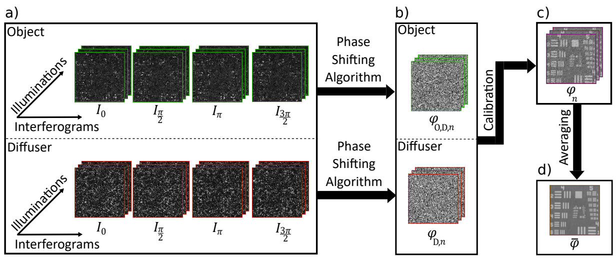

Fig. 2 *Procedure of speckle illumination digital holography.*

Using a phase-shifting algorithm [3], the optical object fields $O_{\mathrm{D},n}(x)$ and the diffuser fields corresponding to diffuser position n are reconstructed from phase-shifted holograms of the object and diffuser. Speckle illumination modulates the sample field multiplicatively: $O_{\mathrm{D},n}(x) = O(x)D_n(x)$. Calibration divides each object field by the corresponding diffuser field, weighted by its amplitude to reduce phase noise: $O_n(x) = \frac{O_{\mathrm{D},n}(x)}{D_n(x)+\epsilon}|D_n(x)|$, with $\epsilon = 10^{-6}$ to prevent division by zero. Residual phase errors are mitigated by averaging over N decorrelated diffuser positions: $\overline{O}(x) = \frac{1}{N}\sum_{n=1}^{N} O_n(x)$.

4 Experiment

Experiments were performed using a USAF 1951 test target with a 105 nm chrome layer. $\mathrm{NA}_{\mathrm{illu}}$ was set to 0.02 and 0.04, while $\mathrm{NA}_{\mathrm{obj}}$ was fixed at 0.05. The corresponding mean speckle sizes δ_S were $39.0\,\mu\mathrm{m}$ and $19.5\,\mu\mathrm{m}$, respectively. For each $\mathrm{NA}_{\mathrm{illu}}$, 100 diffuser positions were used with step sizes

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equal to the speckle size. Additionally, 100 holograms with plane-wave illumination were acquired and their optical fields averaged for comparison.

5 Results

The experiment validates the Abbe resolution criterion [4], where resolution is given by $\delta_{\mathrm{res}} = \lambda/\mathrm{NA}_{\mathrm{total}}$, with $\mathrm{NA}_{\mathrm{total}} = \mathrm{NA}_{\mathrm{obj}} + \mathrm{NA}_{\mathrm{illu}}$. For plane-wave illumination, $\mathrm{NA}_{\mathrm{illu}} = 0.00$. Table 1 lists the theoretical resolution limits.

$\mathrm{NA}_{\mathrm{total}}$	Resolution [μm]	Resolvable Group
0.05	15.60	6:1
0.07	11.14	6:3
0.09	8.67	6:6

Tab. 1 *Theoretical resolution for different* $\mathrm{NA}_{\mathrm{total}}$

The results are shown in Figure 3.

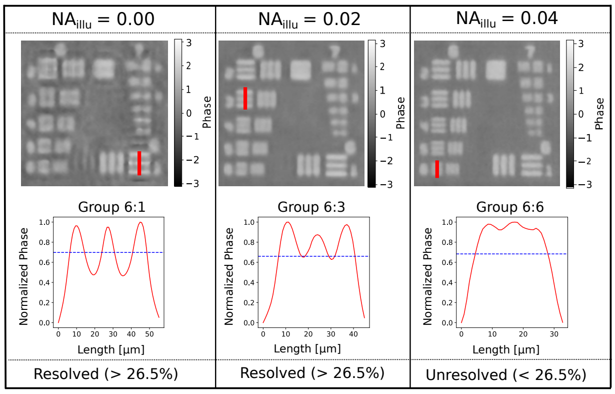

Fig. 3 *USAF Test Target Results. Top: 2D phase images of USAF groups 6 and 7 for various* $\mathrm{NA}_{\mathrm{illu}}$ *values, with expected resolvable groups marked by red lines indicating one-dimensional profiles. Bottom: Plots of these profiles with a 26.5% threshold (blue dashed line) for objective resolution.*

Phase images of USAF groups 6 and 7 were analyzed. Resolution was assessed using line profiles, with a 26.5% modulation depth threshold. Resolution enhancement was confirmed for $\mathrm{NA}_{\mathrm{illu}} = 0.02$, but structures at $\mathrm{NA}_{\mathrm{illu}} = 0.04$ were not resolved according to this objective metric.

6 Discussion

SIDH improves lateral resolution by using a diffuser to create speckle patterns with greater angular diversity than plane-wave illumination. This shifts higher spatial frequencies into the objective's aperture, increasing the total numerical aperture $(\mathrm{NA}_{\mathrm{total}})$. By dividing the object's optical field by the diffuser's field, as described in the calibration process, these frequencies are restored, making the enhanced resolution visible. Higher $\mathrm{NA}_{\mathrm{illu}}$ values further improve resolution, as demonstrated with the USAF test target, where higher groups are resolved. However, for $\mathrm{NA}_{\mathrm{illu}} = 0.04$, while the group appears subjectively resolved, the phase modulation is too low to be objectively classified as resolved. This occurs because increasing the ratio of $\mathrm{NA}_{\mathrm{illu}}$ to $\mathrm{NA}_{\mathrm{obj}}$ makes the system's transfer function resemble that of an incoherent system, enhancing resolution but reducing contrast, making groups harder to resolve clearly [5, 6].

7 Outlook and Conclusion

Experimental results confirm improved resolution, but higher $\mathrm{NA}_{\mathrm{illu}}$ reduces contrast, limiting theoretical resolution gains. Future advancements, such as ring-shaped illumination or iterative reconstruction, could further enhance resolution while addressing contrast loss, advancing SIDH's potential for high-resolution holographic imaging.

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