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Research Article

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Posted Date: October 22nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11270204/v1>

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Additional Declarations: No competing interests reported.

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Abstract

Digital holography enables full-field surface reconstruction with high axial sensitivity, but coherent illumination makes it susceptible to parasitic reflections. We present a multi-wavelength method using spatially diverse speckle illumination to suppress reflections from axially displaced interfaces while extending the unambiguous height range. At each wavelength, phase-shifting holograms are recorded for independent speckle realizations. The reconstructed object fields are calibrated with matching mirror-reference fields and coherently averaged. Owing to the finite axial correlation length of the speckle field, contributions from the selected reconstruction plane are preserved, whereas displaced contributions decorrelate and are progressively suppressed. Measured axial correlation widths for illumination numerical apertures of 0.02, 0.04, and 0.08 agree well with theory. For a microscope slide, averaging 100 realizations at an illumination numerical aperture of 0.08 reduces normalized amplitude noise and phase noise by factors of approximately five and six relative to plane-wave illumination. For a coin viewed through a coverslip, spatial height noise decreases from 54.3 μm to

5.1 μm while preserving surface features. Three gauge-block surfaces spanning 20.5 mm are reconstructed with mean relative heights agreeing with nominal values within 2 μm . The method retains numerical refocusing without mechanical axial scanning.

Keywords: digital holography, speckle illumination, parasitic reflection suppression, multi-wavelength interferometry, synthetic wavelength, metrology

1 Introduction

Digital holography (DH) uses interferometric principles to record an interference pattern from which the complex optical field, including amplitude and phase, can be reconstructed numerically. It thereby enables non-contact, full-field surface topography reconstruction with subwavelength axial resolution [1, 2]. Numerical propagation of the reconstructed wavefield along the optical axis further allows computational refocusing, making DH a versatile technique for high-precision dimensional metrology and quantitative phase imaging of technical and biological specimens [3–5].

Interferometric acquisition requires sufficient mutual coherence between the object and reference waves. Consequently, highly coherent laser sources are commonly employed in DH. Their long coherence length, however, introduces substantial drawbacks, as reflections from optical surfaces, sample substrates, and multiply scattered light can interfere with the desired object wave at the detector. These unwanted contributions produce coherent artifacts that degrade the fidelity of the reconstructed complex wavefield.

A common strategy for suppressing such artifacts is to reduce the temporal or spatial coherence of the illumination, for example by using light-emitting diodes (LEDs) or rotating diffusers [6–8]. Although these approaches effectively suppress coherence-induced artifacts and parasitic interference, they introduce substantial trade-offs. Temporally low-coherence illumination requires precise optical-path-length matching between the object and reference arms. Furthermore, the short coherence length inherently restricts the axial depth range over which interferometric signals can be recorded. Similarly, time-averaged reduced spatial coherence generated by a rotating diffuser can lead to a distance-dependent loss of spatial resolution during numerical propagation [6]. Consequently, both methods can reduce the usable depth range for interferometric imaging and computational refocusing.

Alternatively, rather than physically reducing the illumination coherence, an effective coherence reduction can be synthesized computationally while retaining an extended numerical refocusing range. Kosmeier et al., for example, recorded holograms at multiple wavelengths and numerically superimposed the reconstructed complex fields to synthesize a short effective coherence length [9]. By itself, however, simple field superposition does not provide the extended unambiguous measurement range associated with synthetic-wavelength techniques. Conventional multi-wavelength digital holography (MWDH) exploits phase differences between optical wavelengths to generate synthetic wavelengths, thereby extending the unambiguous height range and

enabling the characterization of steep or large-scale surface topographies [5, 10]. Nevertheless, because conventional MWDH typically relies on coherent illumination, it remains susceptible to parasitic reflections, multiple scattering, and coherent artifacts.

In this work, we introduce multi-wavelength speckle-illumination digital holography (MWSIDH), which combines the extended unambiguous height range of MWDH with the computational suppression of parasitic interference using spatially diverse speckle illumination (SI). Building on SI approaches previously established in DH [11–17], holograms at each wavelength are recorded under multiple statistically independent speckle realizations. After calibration with mirror-reference fields recorded for the corresponding illumination patterns, coherent contributions originating from interfaces axially displaced from the selected object plane are effectively decorrelated and are progressively suppressed through coherent averaging. The multi-wavelength acquisition further enables hierarchical phase unwrapping based on a sequence of synthetic wavelengths. This approach provides a multi-centimeter unambiguous height range with micrometer-scale precision, enabling the reconstruction of macroscopic topographies while substantially suppressing parasitic interference and retaining numerical refocusing without mechanical axial scanning.

2 Optical Setup and Data Acquisition

The experimental system builds upon the speckle-illumination digital holography setup reported previously [16, 17] and was extended to enable multi-wavelength acquisition and continuous wavelength monitoring. A schematic representation of the experimental MWSIDH setup is shown in Fig. 1. The system comprises two laser sources. Laser 1 is a tunable distributed-feedback laser diode (TOPTICA, DFB pro L, LD-0785-0100-DFB-2) with a center wavelength of 785 nm, an output power of 100 mW, and a typical mode-hop-free tuning range of 2.2 nm. Laser 2 is a distributed-Bragg-reflector laser diode (TOPTICA, DBR pro L, LD-0780-0120-DBR-2) operating at a fixed wavelength $\lambda_s = 780.485$ nm. Together, these sources provide a total of eight discrete wavelengths, selected to generate a progressively decreasing sequence of synthetic wavelengths for hierarchical phase unwrapping, as detailed in Sec. 3.4. Their distribution represents a trade-off among the wavelength ranges available from the two laser sources, a sufficiently large initial unambiguous height range, and low height uncertainty in the final reconstruction. The selected wavelengths are listed in Table 1.

The outputs of both lasers are coupled into a fiber switch (FS), enabling sequential selection of the illumination wavelength. The output fiber is split via a fiber beam splitter (FBS). Because knowledge of the absolute emission wavelengths with picometer-scale precision is required, one output directs a fraction of the optical power to a high-precision wavemeter (WM; HighFinesse WS7-60) for continuous wavelength monitoring. The other output supplies the free-space interferometer.

The divergent beam emerging from the fiber is collimated by a lens (L1) and divided by a beam splitter (BS) into the reference and object arms. In the object arm, the collimated beam passes through a holographic diffuser, producing a fully developed speckle field. A $4f$ optical configuration with unit magnification, comprising two identical two-element lens assemblies (L2) each with an effective focal length of

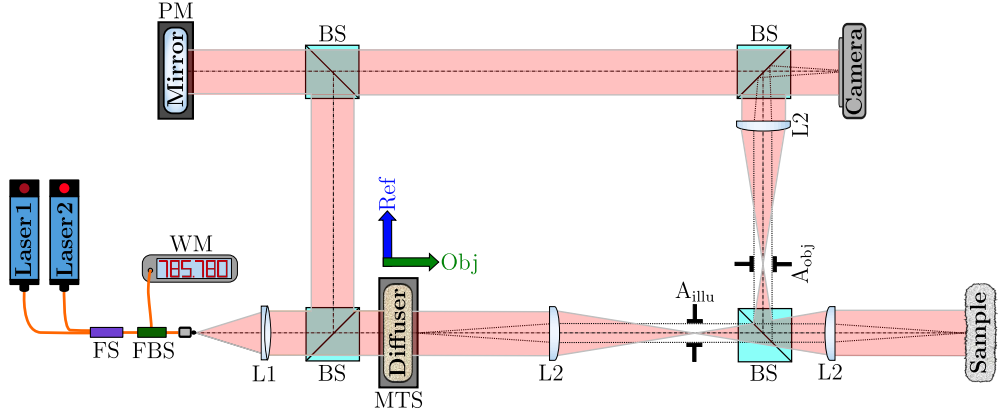


Fig. 1 Schematic diagram of the experimental setup. FS: fiber switch; FBS: fiber beam splitter; WM: wavemeter; L1: collimating lens; L2: two-element lens assembly; BS: beam splitter; MTS: motorized translation stage; A_{illu} : illumination aperture; A_{obj} : object-side aperture; PM: piezoelectric motor. Adapted from [16, 17].

Table 1 Emission wavelengths λ_j used for the multi-wavelength measurements.

Laser Source	Index j	λ_j/nm
Laser 1	1	785.780
	2	785.772
	3	785.757
	4	785.710
	5	785.500
	6	784.870
	7	783.886
Laser 2	8	780.485

$f_2 = 240$ mm, projects the speckle pattern onto the specimen plane. An iris aperture, A_{illu} , located in the Fourier plane of this $4f$ configuration defines the illumination numerical aperture, NA_{illu} , and thus controls the speckle size at the specimen.

The backscattered light from the specimen surface is collected and imaged onto the sensor of a monochrome CMOS camera (Ximea, MC124MG-SY) using a second, identical $4f$ system. The camera has an active sensor area of 4112×3008 pixels with a pixel pitch of $3.45 \mu\text{m}$, corresponding to an effective field size of approximately $14.20 \text{ mm} \times 10.40 \text{ mm}$. A second iris aperture, A_{obj} , positioned in the Fourier plane of the imaging system defines the object-side numerical aperture, which is fixed at $\text{NA}_{\text{obj}} = 0.08$.

The reference beam is subsequently recombined with the backscattered object field at the camera sensor using two additional beam splitters and a mirror. On-axis holograms are acquired using a four-step phase-shifting scheme with phase increments of

$\pi/2$. The phase shifts are generated by translating the mirror via a piezoelectric motor (PM; Thorlabs, NFL5DP20S). A mirror displacement of $\lambda/8$ produces an optical-path-length change of $\lambda/4$ in reflection and, consequently, the required phase increment of $\pi/2$. To generate spatially decorrelated speckle realizations, the holographic diffuser is mounted on a motorized translation stage (MTS; Physik Instrumente M-126) providing micrometer-scale lateral positioning. The characteristic lateral speckle size at the specimen plane is diffraction-limited by the illumination aperture and can be estimated as [14, 18]

$$\delta_S \approx \frac{\lambda}{NA_{\text{illu}}}. \quad (1)$$

To ensure that successive illumination patterns are effectively decorrelated, the lateral translation step of the diffuser was chosen to exceed the characteristic speckle size δ_S . The translation steps used for the investigated illumination numerical apertures are summarized in Table 2.

Table 2 Lateral diffuser translation steps between successive acquisitions for the investigated illumination numerical apertures NA_{illu} .

NA_{illu}	Diffuser translation step / μm
0.02	41
0.04	21
0.08	11

For each wavelength, holograms are acquired at all predefined diffuser positions. The illumination wavelength is then changed, and the same sequence of diffuser positions is repeated. For calibration and characterization of the speckle statistics, the specimen is replaced by a planar mirror positioned in the object plane, and the complete acquisition sequence is repeated using the same diffuser positions and wavelengths. Furthermore, conventional plane-wave illumination (PWI) holograms are obtained by removing the holographic diffuser from the optical path.

3 Reconstruction and Processing in Multi-Wavelength Speckle Illumination Digital Holography

An overview of the MWSIDH workflow is shown in Fig. 2. For both the specimen and mirror-reference measurements, phase-shifted interferograms are recorded at each illumination wavelength and diffuser position. The corresponding complex fields are then reconstructed using an on-axis phase-shifting algorithm. Subsequently, the object fields are calibrated with the corresponding mirror-reference fields and coherently averaged over all diffuser positions. Finally, hierarchical multi-wavelength phase unwrapping is applied to recover the surface-height distribution.

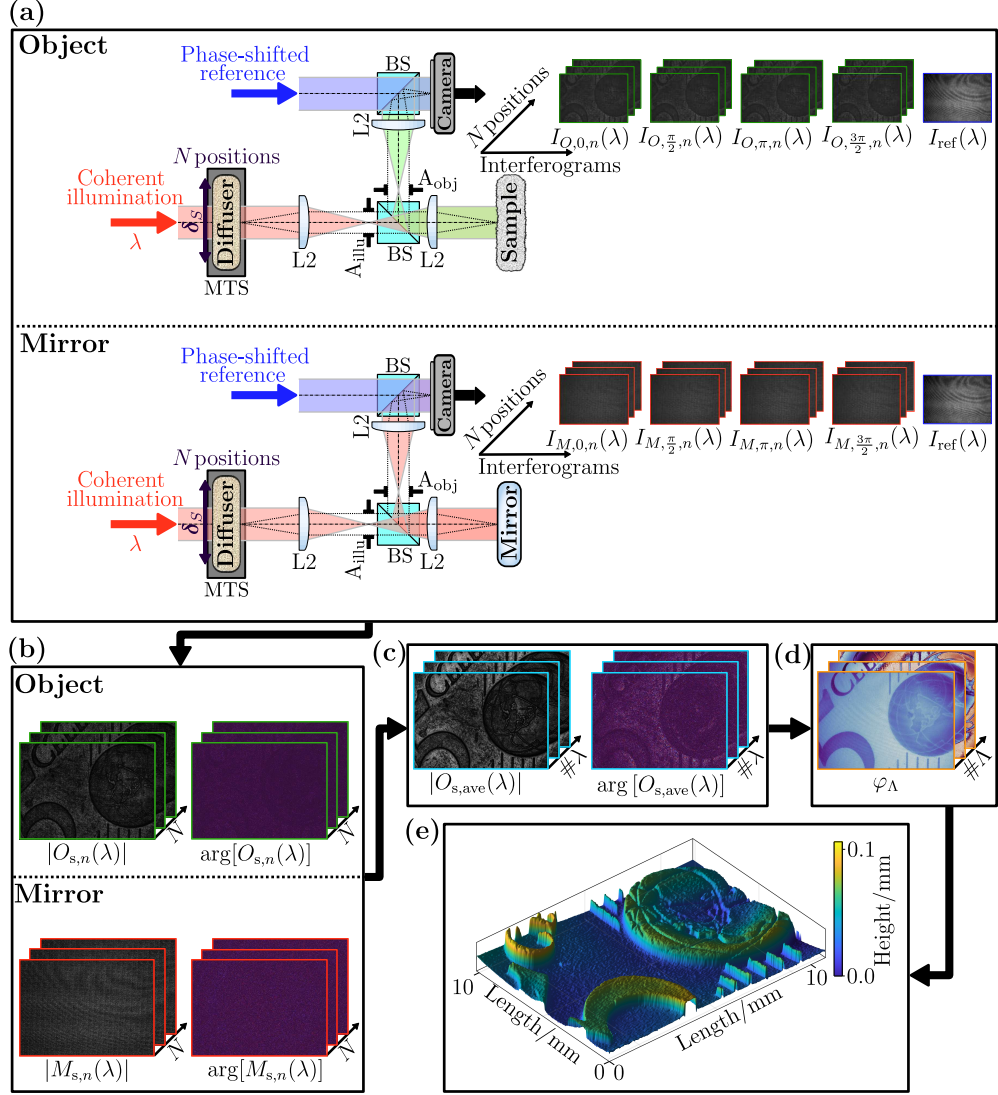


Fig. 2 Overview of the multi-wavelength speckle illumination digital holography (MWSIDH) workflow. (a) Acquisition of phase-shifted object I_O and mirror-reference I_M interferograms at multiple wavelengths λ for N diffuser positions. (b) Reconstructed complex object fields $O_{s,n}(\lambda)$ and mirror-reference fields $M_{s,n}(\lambda)$. (c) Calibrated and coherently averaged complex backscattering coefficient $O_{s,ave}(\lambda)$ for different wavelengths λ . (d) Synthetic phase maps for synthetic wavelengths Λ . (e) Reconstructed surface height after hierarchical multi-wavelength phase unwrapping.

3.1 Phase-Shifting Complex-Field Reconstruction

The complex object field at the camera sensor plane is reconstructed from the on-axis interferograms using a four-step phase-shifting algorithm [19]. For the n th diffuser position and illumination wavelength λ , the reconstructed field $O_{s,n}(x, y; \lambda)$ is given by [20, 21]

$$O_{s,n}(x, y; \lambda) = \frac{[I_{O,0,n} - I_{O,\pi,n}] + i \left[I_{O,\frac{\pi}{2},n} - I_{O,\frac{3\pi}{2},n} \right]}{4\sqrt{I_{\text{ref}}}}, \quad (2)$$

where $I_{O,0,n}$, $I_{O,\frac{\pi}{2},n}$, $I_{O,\pi,n}$, and $I_{O,\frac{3\pi}{2},n}$ are the object interferograms recorded with relative phase shifts of 0, $\pi/2$, π , and $3\pi/2$, respectively. Here, (x, y) denotes the lateral coordinates in the reconstructed field plane. The spatial and spectral dependencies of the interferograms are omitted for clarity. The reference-beam intensity I_{ref} is determined for each wavelength from a separate measurement with the object arm blocked. The same reconstruction procedure is applied to the mirror-reference measurements, $M_{s,n}(x, y; \lambda)$, as well as to recordings acquired under PWI, $O_{\text{pw},n}(x, y; \lambda)$ and $M_{\text{pw},n}(x, y; \lambda)$. For the PWI measurements, where the diffuser is removed, the index n denotes successive repeated acquisitions recorded over time under otherwise identical conditions.

3.2 Numerical Propagation and Refocusing

For objects extending beyond the depth of focus, the reconstructed complex fields are numerically propagated along the optical axis using the angular-spectrum method. The axial coordinate z is defined in the specimen space relative to the plane optically conjugate to the camera sensor. This nominal in-focus plane establishes the origin $z = 0$ and coincides with the plane of initial digital reconstruction, with positive z values pointing toward the imaging system. The object field $O_{s,n}(x, y, 0; \lambda)$ propagated to an axial position z is given by [21, 22]

$$O_{s,n}(x, y, z; \lambda) = \mathcal{F}^{-1} \{ \mathcal{F} [O_{s,n}(x, y, 0; \lambda)] H(f_x, f_y; z, \lambda) \}, \quad (3)$$

where $\mathcal{F}$ and $\mathcal{F}^{-1}$ denote the two-dimensional forward and inverse Fourier transforms, respectively, and f_x and f_y represent the transverse spatial frequencies. The angular spectrum transfer function is defined as

$$H(f_x, f_y; z, \lambda) = \begin{cases} \exp \left[i \frac{2\pi z}{\lambda} \sqrt{1 - (\lambda f_x)^2 - (\lambda f_y)^2} \right], & \text{for } f_x^2 + f_y^2 \leq \frac{1}{\lambda^2}, \\ 0, & \text{otherwise.} \end{cases} \quad (4)$$

The same propagation formalism can be applied to the corresponding mirror-reference fields and to fields acquired under PWI.

3.3 Calibration and Coherent Averaging

Because speckle illumination can extend the accessible spatial-frequency bandwidth and thereby improve lateral resolution [11, 13, 16], each propagated complex field

is numerically upsampled by a factor of two in both lateral dimensions via zero-padding in the Fourier domain. This operation provides a finer spatial sampling grid for the subsequent processing while preserving the spatial-frequency content of the reconstructed field. The same upsampling is applied identically to both the object and mirror-reference fields. To compensate for the spatially varying speckle illumination, each propagated object field is calibrated using the corresponding mirror-reference field at the same wavelength, diffuser position n , and axial position z . The calibrated fields are then coherently averaged over all N diffuser positions according to [15, 17]

$$O_{s,\text{ave}}(x, y, z; \lambda) = \frac{\sum_{n=1}^N O_{s,n}(x, y, z; \lambda) M_{s,n}^*(x, y, z; \lambda)}{\sum_{n=1}^N |M_{s,n}(x, y, z; \lambda)|^2}, \quad (5)$$

where the asterisk denotes complex conjugation, and the resulting quantity $O_{s,\text{ave}}(x, y, z; \lambda)$ represents the coherently averaged complex backscattering coefficient of the specimen at the axial position z . The multiplication in the numerator compensates for the phase profile of the incident speckle pattern while inherently introducing an amplitude-dependent weighting. Because regions with low mirror-reference amplitude generally exhibit increased phase noise, this operation downweights their contribution to the average, while the denominator provides the corresponding normalization by the total mirror-reference-field intensity.

3.4 Hierarchical Multi-Wavelength Phase Unwrapping

Combining phase measurements acquired at two different wavelengths, λ_i and λ_j , generates a synthetic wavelength [10]

$$\Lambda_{ij} = \frac{\lambda_i \lambda_j}{|\lambda_i - \lambda_j|}. \quad (6)$$

Because Λ_{ij} can be several orders of magnitude larger than the fundamental wavelengths, it substantially extends the unambiguous height range. The synthetic phase is then calculated as

$$\varphi_{ij}(x, y, z) = \arg [O_{s,\text{ave}}(x, y, z; \lambda_i) O_{s,\text{ave}}^*(x, y, z; \lambda_j)], \quad (7)$$

where $\arg(\cdot)$ denotes the complex argument. For a measurement in reflection geometry, the corresponding surface height can be calculated as

$$h_{ij}(x, y, z) = \frac{\Lambda_{ij}}{4\pi} \varphi_{ij}(x, y, z). \quad (8)$$

In the following, a positive height denotes a displacement of the specimen surface toward the imaging system. For brevity, the explicit dependence of subsequent height estimates on the spatial coordinates (x, y, z) is omitted. In reflection geometry, the 2π -periodicity of $\arg(\cdot)$ causes the directly evaluated height h_{ij} to be intrinsically wrapped into the interval $(-\Lambda_{ij}/4, \Lambda_{ij}/4]$, corresponding to an unambiguous height range of

$\Lambda_{ij}/2$. The wrapped height estimate is subsequently denoted by $h_{ij}^{(w)}$. Although a single long synthetic wavelength can be chosen to provide a large unambiguous height range, the corresponding height uncertainty increases in proportion to the synthetic wavelength.

To address this limitation, a hierarchical multi-wavelength phase-unwrapping strategy is employed [23, 24]. First, the longest synthetic wavelength is used to obtain a coarse, unambiguous measurement of the surface topography. This measurement then guides the unwrapping of progressively shorter synthetic wavelengths, which provide greater height sensitivity and lower height uncertainty. Provided that the unambiguous height range of the longest synthetic wavelength Λ_{12} covers the complete expected surface-height variation, its wrapped estimate is already unambiguous and can be used as the initial unwrapped estimate, such that $h_{12}^{(uw)} = h_{12}^{(w)}$. For example, a wrapped height measurement $h_{13}^{(w)}$ obtained using the shorter synthetic wavelength Λ_{13} can be unwrapped using the coarser measurement $h_{12}^{(uw)}$ according to

$$h_{13}^{(uw)} = h_{13}^{(w)} + \frac{\Lambda_{13}}{2} \left\lfloor \frac{h_{12}^{(uw)} - h_{13}^{(w)}}{\Lambda_{13}/2} + \frac{1}{2} \right\rfloor, \quad (9)$$

where $\lfloor \cdot \rfloor$ denotes the floor operator, and the superscripts (w) and (uw) denote a wrapped and an unwrapped height estimate, respectively. This procedure is repeated recursively for progressively shorter synthetic wavelengths until the shortest synthetic wavelength is reached. The longest synthetic wavelength must be sufficiently large to cover the entire expected height range without ambiguity. At the same time, the ratio between successive synthetic wavelengths must be selected such that the coarse measurement reliably identifies the correct ambiguity order of the subsequent phase map. An approximate criterion is

$$\frac{\Lambda_{13}}{\Lambda_{12}} \gg \frac{\delta_\phi}{\sqrt{2}\pi}, \quad (10)$$

where δ_ϕ denotes the phase noise of a measurement acquired at a fundamental wavelength [24].

Since the phase noise is not known a priori, it was experimentally characterized from 100 repeated holographic measurements of a planar mirror under PWI at $\lambda_8 = 780.485$ nm. The temporal standard deviation was calculated independently for each pixel and subsequently averaged over the complete field size, yielding $\delta_\phi = 0.030$ rad. This low phase noise permits relatively large steps between successive synthetic wavelengths while maintaining reliable ambiguity-order determination. The final wavelength selection was additionally constrained by the tuning range and wavelength stability of the laser sources.

The eight fundamental wavelengths listed in Table 1 yield seven synthetic wavelengths when λ_1 is paired successively with $\lambda_2, \dots, \lambda_8$ using Eq. (6). Their corresponding synthetic wavelengths are summarized in Table 3.

Table 3 Synthetic wavelengths Λ_{1j} used for hierarchical unwrapping. The corresponding unambiguous height range is $\Lambda_{1j}/2$.

Synthetic wavelength	Λ_{1j}/mm
Λ_{12}	77.180
Λ_{13}	26.845
Λ_{14}	8.820
Λ_{15}	2.204
Λ_{16}	0.678
Λ_{17}	0.325
Λ_{18}	0.116

4 Theory of Parasitic-Reflection Suppression

4.1 Theoretical Axial Speckle Correlation

The suppression of parasitic reflections by speckle illumination relies on the finite axial correlation length of the speckle field. Speckle patterns observed at closely spaced axial planes are strongly correlated, whereas their correlation decreases with increasing axial separation. Consequently, calibration with the corresponding mirror-reference field followed by coherent averaging preferentially preserves contributions originating from the selected reconstruction plane, while contributions from axially displaced interfaces are increasingly suppressed.

To quantify the axial correlation length, the normalized complex-amplitude correlation coefficient $\mu_A(\Delta z)$ between two on-axis points separated by an axial distance Δz is considered. Assuming a fully developed, delta-correlated speckle field in the pupil plane, the correlation coefficient is given by [25]

$$\mu_A(\Delta z) = \frac{\iint I(u, v) \exp\left[-\frac{ik\Delta z}{2L^2}(u^2 + v^2)\right] du dv}{\iint I(u, v) du dv}, \quad (11)$$

where $k = 2\pi/\lambda$ is the wavenumber, L is the propagation distance from the aperture to the observation plane, (u, v) are the transverse pupil coordinates, and $I(u, v)$ is the pupil-plane intensity distribution.

For a uniformly illuminated circular aperture of diameter D , Eq. (11) has a closed-form solution. Using the paraxial numerical aperture $\text{NA}_{\text{illu}} = D/(2L)$ gives

$$\mu_A(\Delta z) = \exp\left(-\frac{i\pi\text{NA}_{\text{illu}}^2\Delta z}{2\lambda}\right) \text{sinc}\left(\frac{\text{NA}_{\text{illu}}^2\Delta z}{2\lambda}\right), \quad (12)$$

where $\text{sinc}(\xi) = \sin(\pi\xi)/(\pi\xi)$ is the normalized sinc function. The full width at half maximum (FWHM) of $|\mu_A(\Delta z)|$ provides a practical measure of the axial speckle-correlation length. Since $|\text{sinc}(\xi)| = 0.5$ at $|\xi| \approx 0.603$, the FWHM is approximately

$$\Delta z_{\text{FWHM}} \approx \frac{2.4\lambda}{\text{NA}_{\text{illu}}^2}. \quad (13)$$

4.2 Suppression through Speckle Diversity

To illustrate the suppression mechanism, a simplified geometry comprising an object plane located at the axial position $z = z_O$ and an axially displaced parasitic interface at $z = z_P$, such as the surface of a glass substrate, is considered, as shown in Fig. 3. Without loss of generality, the selected object plane is taken as the origin of the axial coordinate, such that $z_O = 0$, while the parasitic interface is located at an axial position $z_P \neq 0$. For clarity, the wavelength dependence is omitted throughout this subsection, and only a single parasitic reflection from the glass substrate is considered. Even in the presence of multiple parasitic interfaces, their complex field contributions are coherently superimposed and individually suppressed according to their respective axial correlation with the selected object plane.

Within this framework, for the n th realization of the speckle illumination, the total complex field $U_{s,n}(x, y)$ reconstructed in the detector plane is modeled as the coherent superposition of the desired object contribution $O_{s,n}(x, y)$ and the parasitic contribution $P_{s,n}(x, y)$ according to

$$U_{s,n}(x, y) = O_{s,n}(x, y) + P_{s,n}(x, y). \quad (14)$$

The complex speckle fields incident on the object and parasitic planes are denoted by $M_{s,n}(x, y, z_O)$ and $M_{s,n}(x, y, z_P)$, respectively. They are represented by the corresponding mirror-reference fields obtained from calibration measurements with a planar mirror. Their mutual correlation decreases as the axial separation $|z_O - z_P|$ increases. In particular, when

$$|z_O - z_P| \gg \Delta z_{\text{FWHM}}, \quad (15)$$

the two speckle fields are effectively decorrelated. Within a linear coherent-imaging model, the reconstructed detector field can be expressed as

$$U_{s,n}(x, y) = g_{\text{obj}}(x, y; z_O) * [M_{s,n}(x, y, z_O)O(x, y; z_O)] \\ + g_{\text{obj}}(x, y; z_P) * [M_{s,n}(x, y, z_P)P(x, y; z_P)], \quad (16)$$

where $O(x, y; z_O)$ and $P(x, y; z_P)$ denote the stationary complex reflectivity distributions of the object and parasitic interface, respectively. The functions $g_{\text{obj}}(x, y; z_O)$ and $g_{\text{obj}}(x, y; z_P)$ are the coherent point-spread functions (PSFs) associated with the corresponding axial planes, and $*$ denotes two-dimensional convolution over (x, y) . Following the calibration procedure defined in Eq. (5), the unnormalized calibration term for a single speckle realization is given by the instantaneous complex mutual

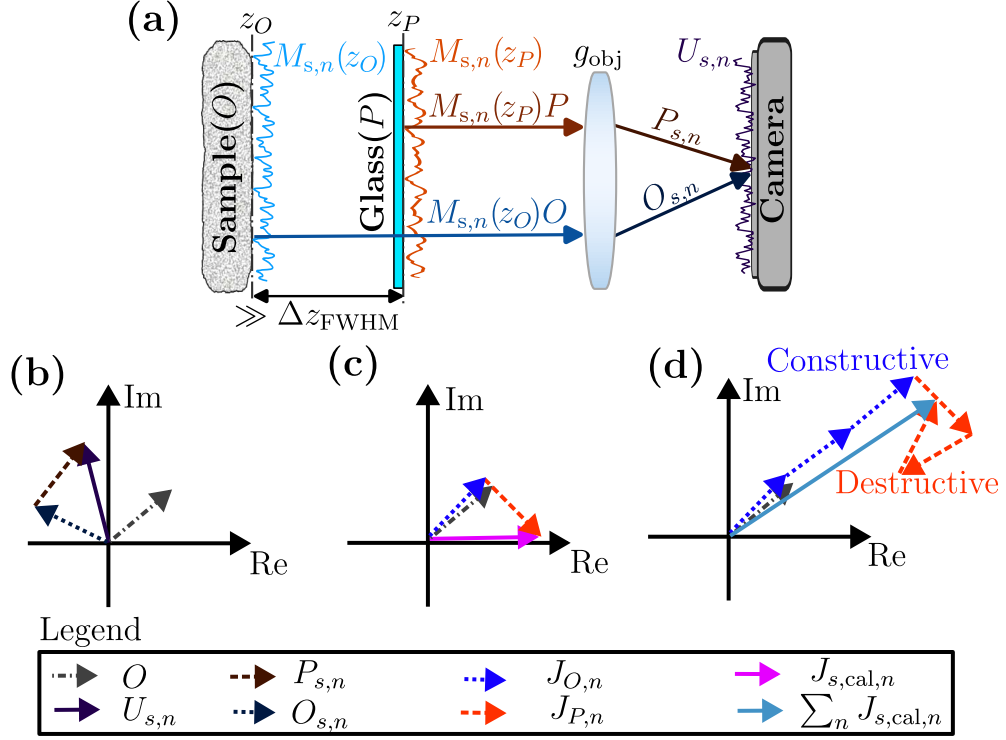


Fig. 3 Principle of parasitic-reflection suppression using spatially diverse speckle illumination. (a) The desired object contribution $O_{s,n}$ originates from the sample plane at z_O , whereas the parasitic contribution $P_{s,n}$ originates from an axially displaced glass interface at z_P , separated by substantially more than the axial correlation width Δz_{FWHM} . The respective planes are illuminated by decorrelated speckle patterns, $M_{s,n}(z_O)$ and $M_{s,n}(z_P)$, producing the backscattered fields $M_{s,n}(z_O)O$ and $M_{s,n}(z_P)P$, which are imaged by the coherent imaging system, represented by the point-spread function g_{obj} , onto the camera to form the total detected field $U_{s,n}$. For simplicity, only a single parasitic interface is considered. (b)–(d) Phasor diagrams illustrating the acquisition, calibration and averaging process. For clarity, all phasors are assigned unit amplitude, and the desired object coefficient O is shown in each diagram as a reference. (b) Phasor representation of the uncalibrated complex field $U_{s,n} = O_{s,n} + P_{s,n}$ recorded at the detector. (c) Instantaneous complex mutual intensity $J_{s,cal,n}$ as the sum of the calibrated object and parasitic contributions, $J_{O,n}$ and $J_{P,n}$. (d) Coherent summation over multiple speckle realizations. The calibrated object contributions add constructively, whereas the decorrelated parasitic contributions undergo a random walk and average toward zero.

intensity between the reconstructed field and the mirror-reference field associated with the object plane as

$$J_{s,cal,n}(x, y) = U_{s,n}(x, y) M_{s,n}^*(x, y, z_O). \quad (17)$$

Substituting Eq. (16) into Eq. (17) yields

$$\begin{aligned} J_{s,cal,n}(x, y) &= \left\{ g_{obj}(x, y; z_O) * [M_{s,n}(x, y, z_O) O(x, y; z_O)] \right\} M_{s,n}^*(x, y, z_O) \\ &\quad + \left\{ g_{obj}(x, y; z_P) * [M_{s,n}(x, y, z_P) P(x, y; z_P)] \right\} M_{s,n}^*(x, y, z_O) \\ &= J_{O,n}(x, y) + J_{P,n}(x, y), \end{aligned} \quad (18)$$

where $J_{O,n}(x, y)$ and $J_{P,n}(x, y)$ represent the calibrated object and parasitic contributions, respectively. The object term correlates the speckle field associated with the object plane with its complex conjugate. Consequently, for a large number N , the averaging process approaches the ensemble average, resulting in the stable, nonzero response

$$\langle J_{O,n}(x, y) \rangle = \left\langle \left\{ g_{obj}(x, y; z_O) * [M_{s,n}(x, y, z_O) O(x, y; z_O)] \right\} M_{s,n}^*(x, y, z_O) \right\rangle. \quad (19)$$

This expectation value can be evaluated from the spatial autocorrelation function of the speckle field. It gives rise to an effective optical transfer function that characterizes the imaging response under speckle illumination [17].

In contrast, the parasitic term involves the cross-correlation of speckle fields originating from two axially separated planes, yielding

$$\langle J_{P,n}(x, y) \rangle = \left\langle \left\{ g_{obj}(x, y; z_P) * [M_{s,n}(x, y, z_P) P(x, y; z_P)] \right\} M_{s,n}^*(x, y, z_O) \right\rangle. \quad (20)$$

If $M_{s,n}(x, y, z_O)$ and $M_{s,n}(x, y, z_P)$ are statistically uncorrelated and have zero mean, their cross-correlation vanishes, such that

$$\langle J_{P,n}(x, y) \rangle = 0. \quad (21)$$

The desired object contribution converges toward its nonzero ensemble average, whereas the mutually uncorrelated parasitic contributions average toward zero. Thus, averaging over multiple independent speckle realizations progressively suppresses parasitic interference while preserving the correlated object contribution. Because the parasitic contribution vanishes only in the ensemble limit, a finite number N of statistically independent speckle realizations leaves a residual complex parasitic contribution. Assuming identically distributed realizations with zero mean and finite variance, the standard deviation of the coherently averaged parasitic contribution decreases

according to the standard error of the mean,

$$\sigma_{P,N} = \frac{\sigma_{P,1}}{\sqrt{N}}, \quad (22)$$

where $\sigma_{P,N}$ denotes the standard deviation of the residual complex parasitic contribution after averaging N realizations, and $\sigma_{P,1}$ denotes the corresponding single-realization value.

5 Experimental Characterization

Four experiments were conducted. First, the axial correlation of the speckle field was measured for different illumination numerical apertures. Second, the suppression of parasitic reflections was quantitatively evaluated using a microscope slide. Third, artifact suppression on a rough, topographic surface was demonstrated with a five-cent coin positioned behind a coverslip. Finally, the extended axial measurement range of MWSIDH was evaluated using three gauge blocks at different axial positions. The specimens and measurement configurations used to characterize the proposed MWSIDH method are shown in Fig. 4.

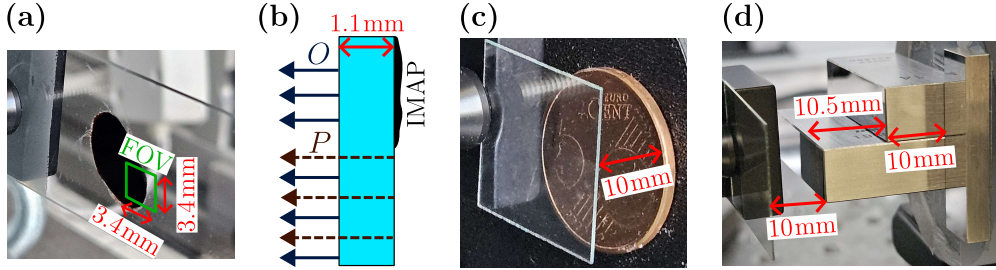


Fig. 4 Specimens and experimental configurations. (a) Microscope slide with the evaluated $3.4 \text{ mm} \times 3.4 \text{ mm}$ field of view (FOV) indicated by the green square. (b) Schematic cross section of the microscope slide with a thickness of approximately 1.1 mm . The front-surface reflection constitutes the desired object signal O , whereas the rear-surface reflection represents the parasitic contribution P . An index-matching absorbing paste (IMAP) was applied to one half of the rear surface within the FOV to suppress P and provide a reference region with a strongly reduced parasitic contribution. (c) Five-cent coin positioned approximately 10 mm behind a coverslip. (d) Three gauge blocks arranged at mutual axial steps of 10.5 mm and 10.0 mm with the coverslip located approximately 10.0 mm in front of the nearest block.

5.1 Axial Speckle Correlation Measurement

The axial speckle correlation relevant to parasitic-reflection suppression was characterized for illumination numerical apertures of $\text{NA}_{\text{illu}} = 0.02, 0.04, \text{ and } 0.08$. A planar mirror was mounted on a motorized translation stage (Thorlabs, LTS150/M) and initially positioned in the nominal in-focus plane $z = 0$ of the imaging system. The mirror was illuminated at $\lambda_8 = 780.485 \text{ nm}$ and translated along the optical axis over a range

of ± 2.5 mm relative to the focal plane. For each value of NA_{illu} , 201 axial positions were evaluated using a step size of 0.025 mm. One phase-shifting hologram sequence was acquired at each position while the diffuser remained stationary. The correlation analysis was performed over the central 1000×1000 camera pixels to reduce the influence of field-dependent aberrations. After reconstruction of the complex fields, their normalized correlation with the field recorded at $z = 0$ was calculated as [25]

$$\mu_A(z) = \frac{\langle M_s(x, y, 0; \lambda_s) M_s^*(x, y, z; \lambda_s) \rangle_{x,y}}{\sqrt{\langle |M_s(x, y, 0; \lambda_s)|^2 \rangle_{x,y} \langle |M_s(x, y, z; \lambda_s)|^2 \rangle_{x,y}}}, \quad (23)$$

where $\langle \cdot \rangle_{x,y}$ denotes spatial averaging over the field of view (FOV). The magnitude $|\mu_A(z)|$ was used to determine the experimental FWHM of the axial speckle correlation. The corresponding theoretical correlation widths calculated using Eq. (13) are listed in Table 4.

Table 4 Theoretical full width at half maximum (FWHM) values of the axial speckle correlation for the investigated illumination numerical apertures NA_{illu} at $\lambda_s = 780.485$ nm.

NA_{illu}	$\Delta z_{\text{FWHM}} / \text{mm}$
0.02	4.683
0.04	1.171
0.08	0.293

5.2 Quantitative Evaluation of Parasitic-Reflection Suppression Using a Microscope Slide

Parasitic-reflection suppression was first quantified using an uncoated microscope slide with a nominal thickness of approximately 1.1 mm and a refractive index of $n_g \approx 1.5$, as shown in Fig. 4(a) and (b). Accounting for double-pass propagation in reflection geometry, the rear-surface reflection corresponds in the paraxial approximation to an effective axial propagation distance of $\Delta z_{g,\text{eff}} = 2 \times 1.1 \text{ mm} / n_g \approx 1.47 \text{ mm}$ in air. The front surface of the slide was positioned in focus and served as the target object plane, whereas the rear surface generated an axially displaced parasitic reflection. At normal incidence, both air-glass interfaces reflect approximately 4% of the incident intensity ($[(n_g - 1)/(n_g + 1)]^2 \approx 0.04$) [18].

Even after accounting for transmission through the front interface, the front- and rear-surface reflections exhibit comparable field amplitudes. These contributions interfere coherently at the camera and can produce substantial distortions in the

reconstructed fields. To obtain a reference measurement with a strongly suppressed rear-surface contribution, an index-matching absorbing paste (IMAP) was applied to one half of the rear surface. This treatment strongly attenuated the rear Fresnel reflection while leaving the front-surface reflection unaffected. The untreated and treated regions could therefore be measured simultaneously, enabling a direct quantitative assessment of the suppression performance. Measurements were performed under PWI and speckle illumination (SI) using $\text{NA}_{\text{illu}} = 0.02, 0.04, \text{ and } 0.08$. For each SI configuration, 100 diffuser positions were recorded at $\lambda_8 = 780.485 \text{ nm}$. For the PWI reference, 100 successive acquisitions were recorded under otherwise identical conditions. Corresponding mirror-reference measurements were acquired for both illumination modes. For each number of averaged acquisitions N , the complex fields were calibrated and coherently averaged according to Eq. (5). The residual phase variation was quantified using the phase noise σ_ϕ , calculated as the spatial standard deviation of the reconstructed phase within selected regions of interest (ROIs). Amplitude variations were characterized using the normalized amplitude noise $\sigma_{A,\text{norm}}$, defined as the spatial standard deviation of the field amplitude normalized by its spatial mean. Both metrics were evaluated independently in the IMAP-treated and untreated regions. Comparing the two regions enabled the residual contribution of the rear-surface reflection and its suppression as a function of N and NA_{illu} to be quantified.

5.3 Topography Measurement of a Five-Cent Coin Through a Coverslip

To demonstrate parasitic-reflection suppression for a rough, topographically structured object, a five-cent coin was positioned in focus, approximately 10 mm behind a microscope coverslip, as shown in Fig. 4(c). Reflections from the front and rear surfaces of the coverslip interfered coherently with the field backscattered by the coin, producing parasitic amplitude and phase modulations. The complete MWSIDH acquisition sequence was performed using all eight wavelengths listed in Table 1. At each wavelength, holograms were acquired at $N = 100$ statistically decorrelated diffuser positions. For comparison, a single PWI acquisition was recorded at each wavelength. To establish a baseline for evaluating reconstruction fidelity in the presence of parasitic reflections, additional measurements were performed after removing the coverslip under otherwise identical conditions for both SI and PWI. Previous studies have shown that changes in the effective transfer function under speckle illumination can bias reconstructed phase values and lead to an underestimation of surface height [15, 17]. This effect becomes increasingly pronounced as NA_{illu} approaches NA_{obj} . Therefore, $\text{NA}_{\text{illu}} = 0.04$ was selected as a compromise between rapid axial decorrelation and transfer-function fidelity. Compared with $\text{NA}_{\text{illu}} = 0.08$, this configuration provides a larger axial correlation length. This correlation length was sufficient to maintain the desired speckle-calibration response across the surface topography of the coin without requiring region-dependent numerical refocusing.

5.4 Extended-Range Measurement of Gauge Blocks

The ability of MWSIDH to combine parasitic-reflection suppression with an extended unambiguous axial measurement range was evaluated using three smooth gauge blocks with known relative axial positions. As illustrated in Fig. 4(d), the blocks were positioned at nominal axial coordinates $z_{O,1} = -10.0$ mm, $z_{O,2} = 0.0$ mm, and $z_{O,3} = 10.5$ mm. Consequently, the resulting specimen extended over a total axial range of approximately 20.5 mm. A coverslip was positioned approximately 10 mm in front of the nearest block to intentionally introduce additional parasitic reflections.

Measurements were acquired using the complete multi-wavelength acquisition sequence under both SI and PWI. For SI, an illumination numerical aperture of $NA_{\text{illu}} = 0.04$ was used, and $N = 100$ statistically decorrelated diffuser positions were recorded at each wavelength. For PWI, one acquisition was recorded at each wavelength.

Because the three block surfaces were separated by distances substantially exceeding the depth of focus of the imaging system, a single reconstruction plane could not provide an adequately focused representation of all three surfaces. The complex fields were therefore numerically refocused to the axial plane of each block using the angular-spectrum propagation method defined in Eq. (3). In the case of PWI, only the object field was numerically refocused because the PWI data were evaluated without mirror-field calibration. For SI, in contrast, both the object field and the corresponding mirror-reference field were refocused to each block plane to match the local speckle illumination. For the two outer blocks, refocusing was performed to the planes at $z_{O,1}$ and $z_{O,3}$, respectively, whereas for the central block at $z_{O,2} = 0.0$ mm, no numerical propagation was required. Refocusing was carried out independently for all wavelengths and, in the case of SI, for all diffuser positions.

Under SI, the illumination field represented by the mirror-reference measurement and the reflected specimen field propagate in opposite physical directions. Accordingly, opposite signs of the propagation distance were used when refocusing the mirror-reference and object fields to a given block plane.

To evaluate the extended unambiguous axial measurement range without the need for applying a spatially varying propagation distance across the FOV, the three block regions were processed separately. For SI, the refocused object and mirror-reference fields were calibrated and coherently averaged according to Eq. (5). This procedure yielded one refocused, averaged backscattering coefficient for each block and wavelength. The refocused PWI fields were processed directly.

ROIs containing the individual block surfaces were subsequently extracted from the corresponding refocused fields and arranged side by side for visualization and combined height analysis. Hierarchical multi-wavelength phase unwrapping was then applied using the complete sequence of synthetic wavelengths listed in Table 3. The recovered axial positions and relative height differences were compared with the known reference values to evaluate the extended-range topography reconstruction.

6 Results

6.1 Measured Axial Speckle Correlation

The measured axial speckle-correlation curves are compared with the theoretical predictions in Fig. 5. Owing to the reflection geometry, an axial displacement of the mirror changes the round-trip propagation distance by twice that amount. The axial coordinates shown in Fig. 5 therefore represent the effective axial displacement. Consequently, translating the stage over a physical range of ± 2.5 mm yields an evaluated effective axial range of ± 5.0 mm. Both the measured and theoretically calculated correlation curves exhibit a pronounced central peak. Outside the central peak, the theoretical correlation curves reach zero at distinct axial positions, whereas the measured correlations exhibit nonzero minima, which can be attributed to the finite evaluation area and deviations from the idealized delta-correlated pupil assumption. Low-amplitude side lobes characteristic of the underlying sinc profile are clearly discernible for $\text{NA}_{\text{illu}} = 0.04$ and $\text{NA}_{\text{illu}} = 0.08$. As the illumination numerical aperture increases, the central correlation peak becomes narrower. The experimentally determined FWHM values are 4.613 mm, 1.174 mm, and 0.303 mm for $\text{NA}_{\text{illu}} = 0.02$, 0.04, and 0.08, respectively. These results agree well with the theoretical values listed in Table 4.

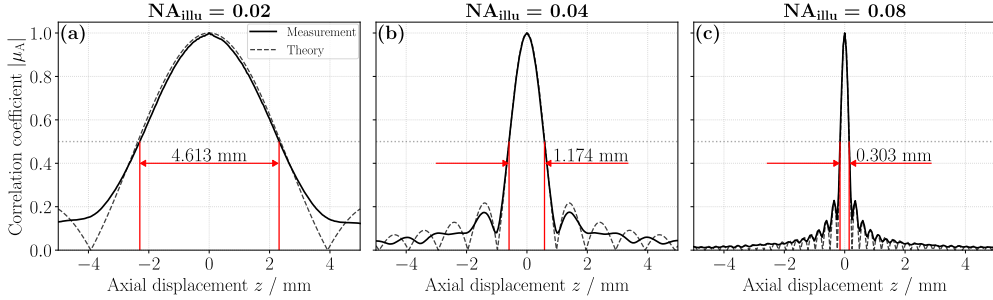


Fig. 5 Measured (solid) and theoretical (dashed) axial speckle-correlation curves for illumination numerical apertures NA_{illu} of (a) 0.02, (b) 0.04, and (c) 0.08. Red markers indicate the measured full width at half maximum (FWHM) of the central correlation peak, which decreases from 4.613 mm via 1.174 mm to 0.303 mm with increasing NA_{illu} . The axial coordinate z accounts for the double-pass propagation in the reflection geometry.

6.2 Parasitic-Reflection Suppression on a Microscope Slide

Figure 6 shows the reconstructed amplitude and phase distributions of the microscope slide after calibration and coherent averaging over $N = 100$ acquisitions. Results are presented for PWI and SI with $\text{NA}_{\text{illu}} = 0.02$, 0.04, and 0.08. For visualization, each amplitude map is normalized to the range from 0 to 1 over the FOV. The left part of the slide, extending from approximately $x = 0$ mm to 1.8 mm, corresponds to the IMAP-treated region. The right part, extending from approximately $x = 1.8$ mm to 3.4 mm,

remains untreated and therefore contains the unsuppressed parasitic contribution from the rear surface.

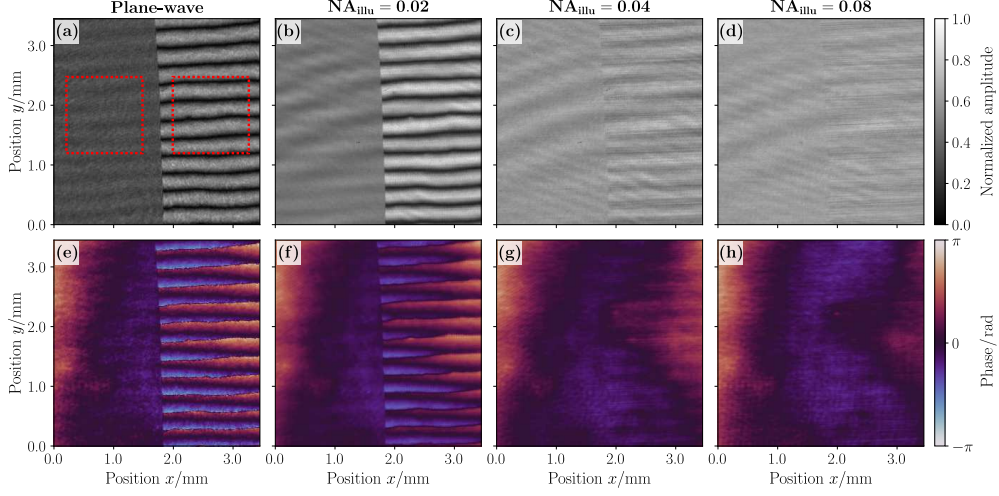


Fig. 6 (a)–(d) Reconstructed amplitude and (e)–(h) phase distributions of the microscope slide after calibration and coherent averaging over $N = 100$ acquisitions, for plane-wave illumination (PWI) and speckle illumination (SI) with $\text{NA}_{\text{illu}} = 0.02, 0.04$, and 0.08 . Each amplitude map is normalized to the range $[0, 1]$. The left region at $x \approx 0$ mm to 1.8 mm is treated with an index-matching absorbing paste (IMAP), whereas the untreated right region at $x \approx 1.8$ mm to 3.4 mm contains the full parasitic contribution from the rear surface. The parasitic fringes decrease with increasing NA_{illu} and are nearly eliminated at $\text{NA}_{\text{illu}} = 0.08$. The red dashed rectangles in (a) indicate the regions of interest (ROIs) used for the quantitative noise evaluation reported in Tables 5 and 6.

Under PWI, pronounced interference fringes are visible in both amplitude and phase within the untreated region. For SI with $\text{NA}_{\text{illu}} = 0.02$, similar yet attenuated artifacts persist. Faint residual fringes are also discernible in the treated region for these two illumination configurations. The fringe contrast decreases systematically with increasing NA_{illu} , becoming substantially reduced at $\text{NA}_{\text{illu}} = 0.04$ and nearly eliminated at $\text{NA}_{\text{illu}} = 0.08$. The latter configuration produces an almost homogeneous amplitude distribution and a smooth phase map in both regions.

The suppression of the parasitic reflection was quantified from the normalized amplitude noise $\sigma_{A,\text{norm}}$ and phase noise σ_ϕ as described in Sec. 5.2. The evaluated areas are indicated by the red dashed rectangles in Fig. 6(a). Tables 5 and 6 summarize the results for a single calibrated acquisition and for the coherently averaged field obtained from $N = 100$ acquisitions.

For $N = 1$ under SI, both $\sigma_{A,\text{norm}}$ and σ_ϕ remain high, with $\sigma_{A,\text{norm}}$ exceeding unity for some configurations. For every investigated illumination configuration, both noise metrics are higher in the untreated region than in the IMAP-treated region.

To ensure a direct comparison based on identical processing, the PWI fields $O_{\text{pw},n}(x, y; \lambda)$ in this experiment were likewise calibrated using a planar mirror-reference measurement $M_{\text{pw},n}(x, y; \lambda)$. Calibration resulted in a slight increase in

Table 5 Phase noise σ_ϕ for a single calibrated acquisition at $N = 1$ and following coherent averaging over $N = 100$ acquisitions. Results are presented for plane-wave illumination (PWI) and speckle illumination (SI) across different illumination numerical apertures NA_{illu} . The evaluation compares the untreated region of the microscope slide with the reference region treated with an index-matching absorbing paste (IMAP).

Illumination	Region	Phase noise σ_ϕ / rad	
		$N = 1$	$N = 100$
PWI	IMAP-treated	0.156	0.156
	Untreated	0.949	0.928
SI, $\text{NA}_{\text{illu}} = 0.02$	IMAP-treated	0.613	0.103
	Untreated	1.127	0.509
SI, $\text{NA}_{\text{illu}} = 0.04$	IMAP-treated	1.256	0.112
	Untreated	1.466	0.166
SI, $\text{NA}_{\text{illu}} = 0.08$	IMAP-treated	0.839	0.130
	Untreated	1.195	0.160

Table 6 Normalized amplitude noise $\sigma_{A,\text{norm}}$ for a single calibrated acquisition at $N = 1$ and following coherent averaging over $N = 100$ acquisitions. Results are presented for plane-wave illumination (PWI) and speckle illumination (SI) across different illumination numerical apertures NA_{illu} . The evaluation compares the untreated region of the microscope slide with the reference region treated with an index-matching absorbing paste (IMAP).

Illumination	Region	Normalized amplitude noise $\sigma_{A,\text{norm}}$	
		$N = 1$	$N = 100$
PWI	IMAP-treated	0.160	0.131
	Untreated	0.537	0.535
SI, $\text{NA}_{\text{illu}} = 0.02$	IMAP-treated	0.870	0.100
	Untreated	1.594	0.396
SI, $\text{NA}_{\text{illu}} = 0.04$	IMAP-treated	1.760	0.086
	Untreated	1.928	0.122
SI, $\text{NA}_{\text{illu}} = 0.08$	IMAP-treated	1.199	0.077
	Untreated	1.718	0.109

both PWI noise metrics. In the IMAP-treated region, σ_ϕ increased from 0.152 rad to 0.156 rad, whereas in the untreated region it increased from 0.939 rad to 0.949 rad. Similarly, $\sigma_{A,\text{norm}}$ increased from 0.143 to 0.160 in the treated region and from 0.534 to 0.537 in the untreated region. This minor degradation may be attributed to the additional measurement noise introduced by the separate mirror-reference acquisition. Mirror-field calibration was therefore omitted for PWI in the subsequent experiments, for which the directly reconstructed PWI fields were used as the conventional reference.

After coherent averaging over $N = 100$ acquisitions, both $\sigma_{A,\text{norm}}$ and σ_ϕ are substantially reduced for all SI configurations. The difference between the treated and untreated regions remains pronounced under PWI and for SI with $\text{NA}_{\text{illu}} = 0.02$, but is greatly reduced for $\text{NA}_{\text{illu}} = 0.04$ and 0.08 . In particular, for $\text{NA}_{\text{illu}} = 0.08$, the residual phase noise in the untreated region decreases to 0.160 rad, approaching the value of 0.130 rad measured in the treated reference region.

Figure 7 shows $\sigma_{A,\text{norm}}$ and σ_ϕ as functions of the number of averaged acquisitions N . A reference curve proportional to $1/\sqrt{N}$ is included to indicate the expected approximate scaling of amplitude and phase fluctuations arising from statistically independent residual parasitic contributions according to Eq. (22). The curve was scaled to the value measured at $N = 5$ for $\text{NA}_{\text{illu}} = 0.08$ in the untreated region. This point was selected because the initial fluctuations associated with single-realization calibration had already decreased, while the residual noise floor had not yet been reached. Since the theoretical FWHM of 0.293 mm for $\text{NA}_{\text{illu}} = 0.08$ is sufficiently small compared with $\Delta z_{g,\text{eff}} \approx 1.47$ mm, this configuration ensures reliable axial decorrelation between the front- and rear-surface contributions.

For $\text{NA}_{\text{illu}} = 0.04$ and 0.08 , the amplitude and phase noise in the untreated region initially decrease approximately according to the expected $1/\sqrt{N}$ dependence before approaching a residual floor. For $\text{NA}_{\text{illu}} = 0.02$, the noise saturates at a substantially higher level. Under PWI, the noise remains approximately constant over the full range of N for both regions and noise metrics, with the treated region at a lower level than the untreated one. Consequently, the discrepancy between the treated and untreated regions is most pronounced under PWI.

In the IMAP-treated region, the SI noise metrics decrease rapidly over the first few realizations and eventually fall below the corresponding PWI levels. At $\text{NA}_{\text{illu}} = 0.02$, the normalized amplitude and phase variations drop below the PWI values after $N = 4$ and $N = 6$ acquisitions, respectively. As NA_{illu} increases to 0.04, the corresponding crossover occurs at $N = 14$ for the amplitude and $N = 18$ for the phase. Finally, for $\text{NA}_{\text{illu}} = 0.08$, the amplitude variation falls below the PWI level at approximately $N = 14$, whereas $N = 45$ realizations are required for the phase variation.

Overall, the results demonstrate that effective suppression requires both a sufficient number of independent speckle realizations and an illumination numerical aperture large enough to decorrelate the speckle fields at the two interfaces. Among the investigated configurations, $\text{NA}_{\text{illu}} = 0.04$ and 0.08 provide the strongest suppression. Compared with PWI in the untreated region, SI with $\text{NA}_{\text{illu}} = 0.08$ at $N = 100$ reduces the normalized amplitude and phase noise by factors of approximately five and six, respectively.

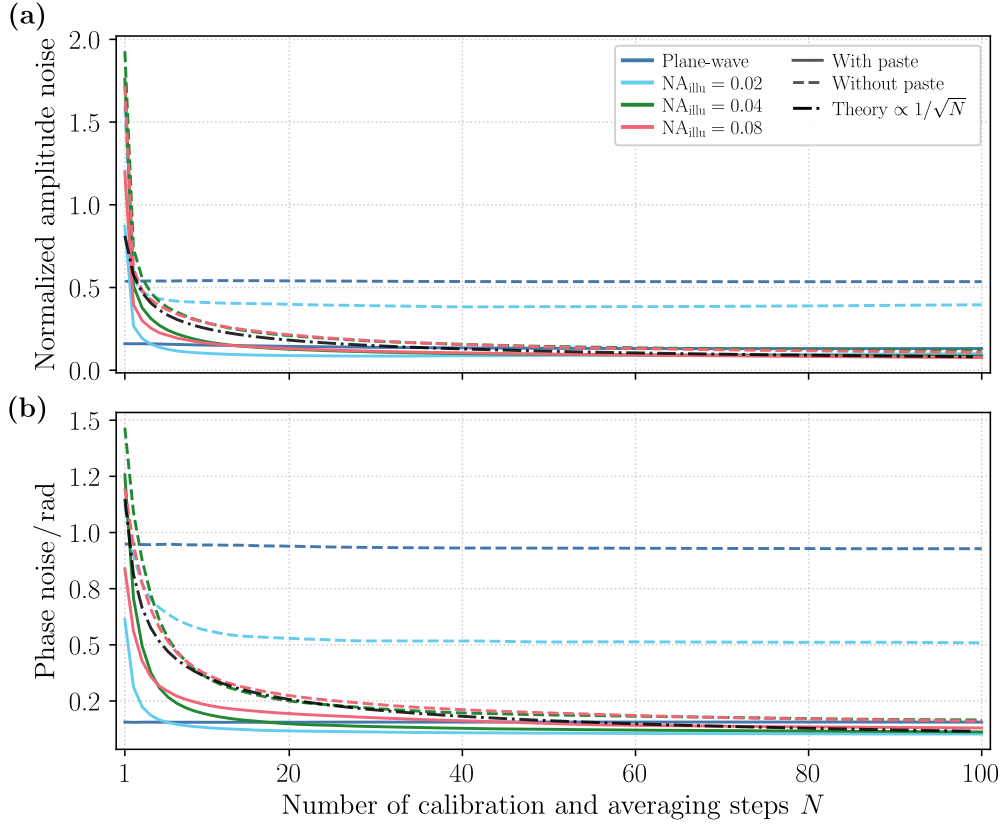


Fig. 7 (a) Normalized amplitude noise $\sigma_{A,\text{norm}}$ and (b) phase noise σ_ϕ as functions of the number of calibrated and coherently averaged acquisitions N . Results are shown for plane-wave illumination (PWI) and speckle illumination (SI) with $NA_{\text{illu}} = 0.02, 0.04$, and 0.08 . Solid and dashed curves represent the index-matching absorbing paste (IMAP) treated and untreated regions of the microscope slide, respectively. Black dash-dotted curves indicate the theoretical $1/\sqrt{N}$ dependence, scaled to the value measured at $N = 5$ for $NA_{\text{illu}} = 0.08$ in the untreated region.

6.3 Topography Reconstruction of a Five-Cent Coin

The reconstructed surface-height distributions of the five-cent coin are shown in Fig. 8. Results obtained under PWI are presented in Fig. 8(a) and (b), whereas the corresponding SI results ($NA_{\text{illu}} = 0.04$, $N = 100$) are shown in Fig. 8(c) and (d). For each illumination mode, measurements were performed without and with the coverslip in front of the coin. A global tilt was removed from each reconstructed height map before visualization and quantitative evaluation.

Without the coverslip, both illumination modes reproduce the main topographic features of the coin over a height range of approximately $0\mu\text{m}$ to $120\mu\text{m}$. In the presence of the coverslip, the height map obtained under PWI exhibits strong spatial fluctuations across the FOV, as shown in Fig. 8(b). Many reconstructed height values lie outside the displayed color range. In contrast, the principal topographic

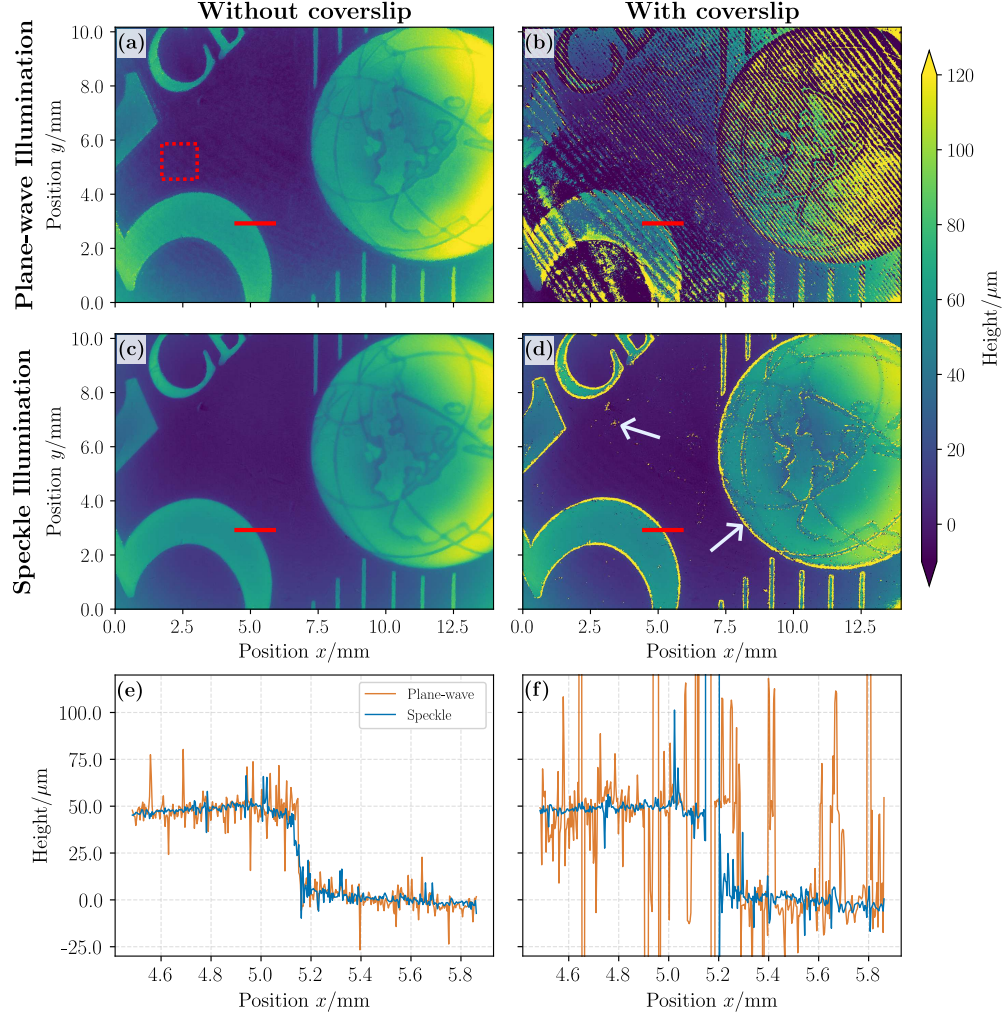


Fig. 8 Reconstructed surface-height distributions of the five-cent coin. (a) Plane-wave illumination (PWI) without the coverslip. (b) PWI with the coverslip. (c) Speckle illumination (SI) without the coverslip. (d) SI with the coverslip. All height maps share the same color scale, and the triangular extensions of the color bar indicate values outside the displayed range. The white arrows in (d) mark examples of isolated height deviations near surface scratches and topographic edges. The red line segments in (a)–(d) indicate the positions of the one-dimensional profiles shown in (e) and (f). (e) Height profiles measured without the coverslip. (f) Height profiles measured with the coverslip. In (e) and (f), the plane-wave and speckle profiles are shown in orange and blue, respectively. The red dashed rectangle in (a) marks the flat region of interest (ROI) used to evaluate the height noise reported in Table 7.

features of the coin remain clearly distinguishable in the SI reconstruction shown in Fig. 8(d). Isolated deviations are nevertheless present, particularly near sharp topographic transitions and surface scratches, examples of which are indicated by white arrows.

Figure 8(e) and (f) show one-dimensional height profiles along the positions marked by the red lines in the corresponding height maps. Each profile crosses an edge of the embossed numeral. Without the coverslip, the PWI and SI profiles reproduce a similar height transition over the interval from $x = 5.1$ mm to 5.2 mm. However, the PWI profile exhibits pronounced local fluctuations, whereas the SI profile displays a noticeably smoother, less noisy edge transition. With the coverslip in place, the PWI profile contains numerous severe deviations, several of which exceed the plotted height range. The SI profile, by contrast, retains the main height transition, with isolated deviations occurring mainly in the vicinity of the edge.

To isolate reconstruction noise from the underlying coin topography, the height noise σ_h , defined as the spatial standard deviation, was evaluated within a nominally flat ROI indicated by the red dashed rectangle in Fig. 8(a). Identical coordinates were used across all datasets, and the results are summarized in Table 7. Without the coverslip, σ_h is 2.416 μm for SI and 5.523 μm for PWI. In the presence of the coverslip, σ_h increases only modestly to 5.129 μm for SI, whereas it increases markedly to 54.255 μm for PWI, demonstrating more than a tenfold noise reduction.

Table 7 Spatial height noise σ_h within the selected coin-surface region of interest (ROI) for plane-wave illumination (PWI) and speckle illumination (SI), measured without and with the coverslip.

Illumination	Spatial height noise σ_h / μm	
	Without coverslip	With coverslip
PWI	5.523	54.255
SI	2.416	5.129

6.4 Extended-Range Reconstruction of Gauge Blocks

Figure 9 shows the amplitude and wrapped-phase distributions obtained after numerically refocusing the reconstructed fields to the axial positions of the three gauge blocks. Each amplitude map is normalized to the range from 0 to 1. The columns correspond to the nominal block positions $z_{O,1} = -10.0$ mm, $z_{O,2} = 0.0$ mm, and $z_{O,3} = 10.5$ mm. For both SI and PWI, refocusing to a given plane produces sharply defined edges and resolves fine surface features, such as microscopic scratches, within the block located at the corresponding reconstruction plane.

Under PWI, the reconstructed amplitude distributions exhibit pronounced interference fringes caused by parasitic reflections from the coverslip surfaces. Correspondingly, spatially structured perturbations appear in the wrapped-phase maps,

particularly near the phase-wrapping boundaries. Under SI, these parasitic artifacts are strongly suppressed, yielding substantially more homogeneous amplitude and phase distributions across the focused block regions.

For each SI reconstruction plane, the in-focus block appears with high amplitude contrast and well-defined phase, whereas the two out-of-focus blocks exhibit strongly attenuated amplitudes and spatially randomized phase. To evaluate all three surfaces over the complete axial range, the in-focus ROIs indicated by the orange (dotted), magenta (dashed), and red (solid) rectangles in Fig. 9(a)–(f) were extracted from the reconstructions refocused to $z_{O,1}$, $z_{O,2}$, and $z_{O,3}$, respectively. These ROIs were then arranged side by side and processed by hierarchical multi-wavelength phase unwrapping for both SI and PWI.

The resulting height distributions are shown in Fig. 10(a) and (b). For each illumination mode, the mean reconstructed height of the central block was subtracted from the complete dataset, thereby defining the central block as the zero-height reference. Both SI and PWI recover the three distinct height levels over the total axial range of approximately 20.5 mm. However, the PWI reconstruction contains severe spatial fluctuations and extreme outliers, several of which exceed the displayed range of ± 11 mm. In contrast, the SI height distributions are nearly uniform within each block ROI.

The mean heights and spatial standard deviations within the extracted block ROIs are summarized in Table 8. Under SI, the reconstructed positions deviate from the nominal values by only 0.002 mm for the first block and 0.001 mm for the third block, with spatial standard deviations between 0.001 mm and 0.002 mm. Under PWI, by contrast, the reconstructed positions of the outer blocks deviate from their nominal values by 0.342 mm and 0.231 mm, respectively, and the spatial standard deviations increase substantially to between 0.409 mm and 1.625 mm.

Figure 10(c) presents one-dimensional height profiles extracted at $y = 0.86$ mm, as indicated by the dash-dotted black lines in panels (a) and (b). The SI profile reproduces the three nominal height levels with low fluctuations, whereas the PWI profile exhibits substantially larger fluctuations and several extreme deviations associated with phase-unwrapping errors.

These results demonstrate that MWSIDH successfully combines the suppression of axially displaced parasitic reflections with numerical refocusing and hierarchical multi-wavelength phase unwrapping. Consequently, under SI, axially separated surfaces spanning more than 20 mm are reconstructed with micrometer-scale accuracy relative to their nominal positions, even in the presence of parasitic reflections.

7 Discussion

7.1 Noise and Reconstruction Fidelity under Speckle Illumination

Under SI, the spatially varying illumination produces pronounced amplitude and phase fluctuations in an individual reconstructed field $O_{s,n}(x, y, z; \lambda)$. Although calibration with the corresponding mirror-reference field $M_{s,n}(x, y, z; \lambda)$ compensates for the spatially varying illumination in principle, a stable estimate of the specimen field requires averaging over multiple statistically independent speckle realizations.

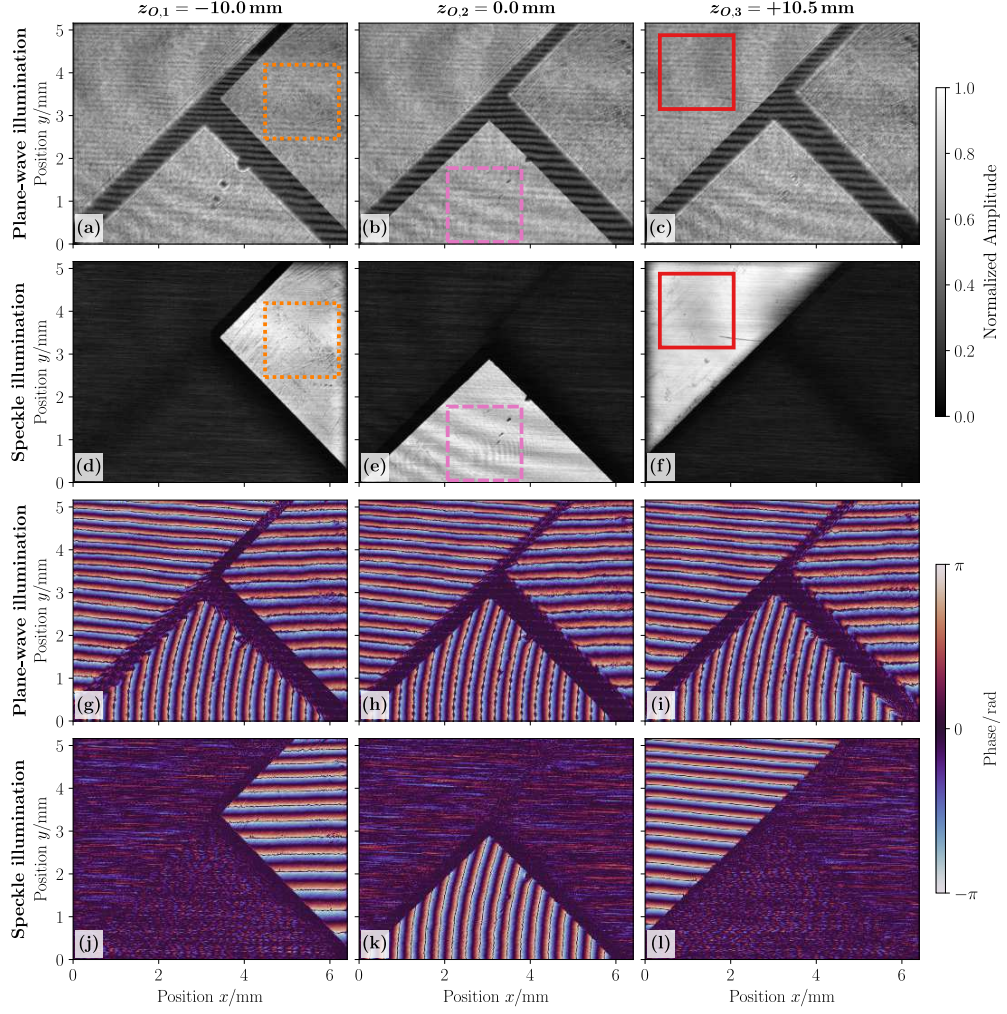


Fig. 9 Numerically refocused amplitude and wrapped-phase distributions of the three gauge blocks under plane-wave illumination (PWI) and speckle illumination (SI). Each amplitude map is normalized to $[0, 1]$. Columns correspond to reconstruction planes at $z_{O,1} = -10.0$ mm, $z_{O,2} = 0.0$ mm, and $z_{O,3} = 10.5$ mm. (a)–(c) Amplitude under PWI; (d)–(f) amplitude under SI; (g)–(i) wrapped phase under PWI; (j)–(l) wrapped phase under SI. Orange (dotted), magenta (dashed), and red (solid) rectangles in (a)–(f) indicate the in-focus regions of interest (ROIs) extracted for subsequent multi-wavelength height reconstruction. Parasitic reflections from the coverslip cause pronounced fringe patterns under PWI, whereas they are effectively suppressed under SI. Concurrently, contributions from out-of-focus block surfaces decorrelate under SI, resulting in strongly attenuated amplitudes and randomized phase distributions.

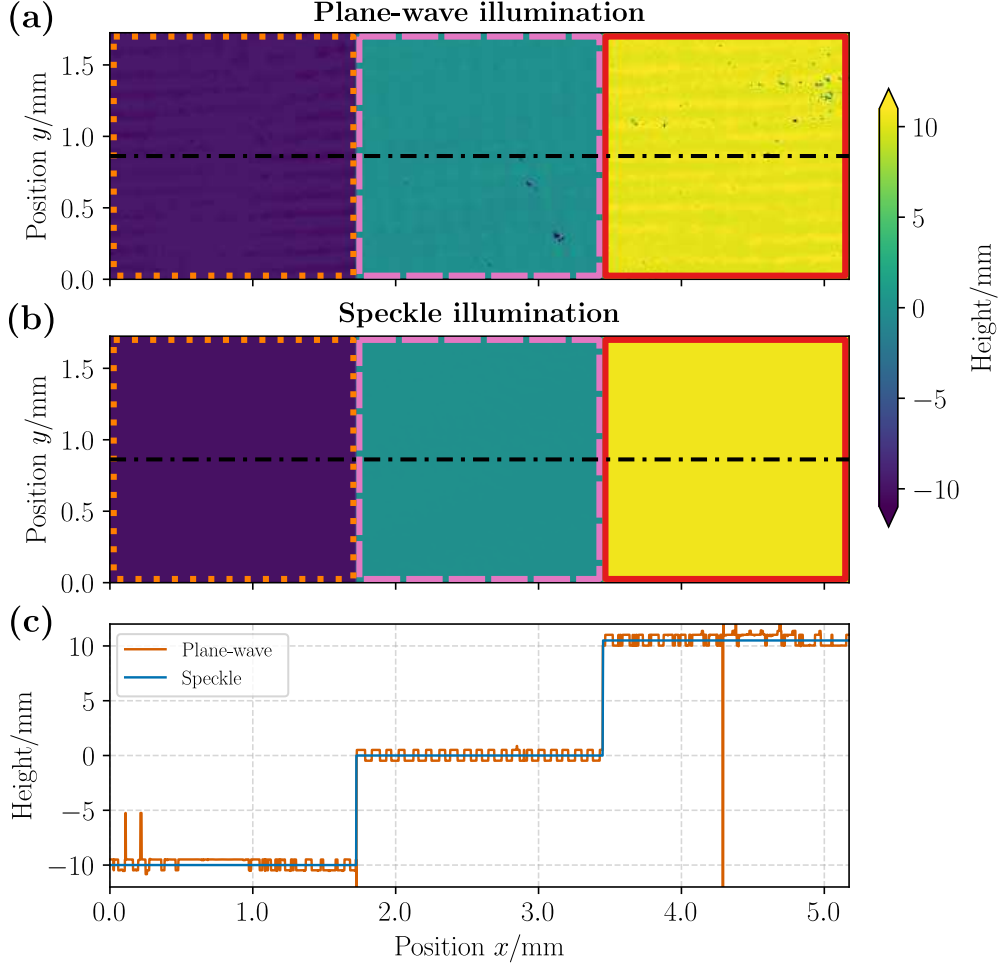


Fig. 10 Extended-range height reconstruction of the three gauge blocks after numerical refocusing, region of interest (ROI) extraction, and hierarchical multi-wavelength phase unwrapping. (a) Height distribution obtained under plane-wave illumination (PWI). (b) Corresponding result obtained under speckle illumination (SI). Orange (dotted), magenta (dashed), and red (solid) rectangles delineate the in-focus ROIs extracted for the blocks at $z_{O,1}$, $z_{O,2}$, and $z_{O,3}$, respectively. The central block defines the zero-height reference. All height maps share the same color scale, and triangular extensions of the color bar indicate values outside the displayed range. (c) One-dimensional height profiles extracted at $y = 0.86$ mm along the dash-dotted black lines in (a) and (b), with PWI and SI plotted in orange and blue, respectively. Speckle illumination accurately reproduces the three nominal height steps while eliminating the severe spatial fluctuations and unwrapping errors visible under PWI.

Table 8 Nominal and reconstructed heights of the three gauge-block reference surfaces under plane-wave illumination (PWI) and speckle illumination (SI). The central block serves as the zero-height reference. Reconstructed values are reported as spatial mean $\pm$ standard deviation within the corresponding region of interest (ROI).

Reference surface	Height h / mm		
	Nominal	PWI	SI
Block 1 ($z_{O,1}$)	-10.000	-9.658 ± 0.409	-9.998 ± 0.001
Block 2 ($z_{O,2}$)	0.000	0.000 ± 0.803	0.000 ± 0.002
Block 3 ($z_{O,3}$)	10.500	10.269 ± 1.625	10.501 ± 0.001

As shown in Tables 5 and 6, a single calibrated SI field exhibits larger amplitude and phase variations than the corresponding PWI field. For $N = 1$, Eq. (5) locally reduces to a division by the mirror-reference field. Consequently, measurement noise in both the specimen and mirror-reference fields can be strongly amplified in regions where the reference-field amplitude is low. With increasing N , the specimen fields are combined using an amplitude-dependent weighting determined by the corresponding mirror-reference fields. Contributions associated with low reference amplitudes are thereby downweighted, progressively reducing the resulting fluctuations.

With increasing N , the SI noise levels in the IMAP-treated region of the microscope slide fall below the corresponding PWI levels, as evident from Fig. 7. Similar reductions in coherent artifacts and phase noise using SI in DH have been reported previously, with the phase noise likewise decreasing below the PWI level after several acquisitions [11, 12, 14].

The different convergence rates observed for the investigated values of NA_{illu} may partly result from imperfect reproduction of the corresponding speckle fields between the specimen and mirror-reference measurements. Higher illumination numerical apertures produce smaller speckle grains, which are expected to be more sensitive to small lateral and axial positioning errors of the diffuser. Such mismatches can produce residual local phase errors and may contribute to the comparatively slow decrease of the phase noise for $NA_{\text{illu}} = 0.08$, as shown in Fig. 7(b).

The coin measurements performed without the deliberately introduced coverslip provide an additional comparison of the two illumination modes. Within the evaluated ROI, SI yields a lower spatial height variation than PWI, as summarized in Table 7. This reduction may result from the suppression of coherent artifacts originating elsewhere in the optical system. Because the coin is not a calibrated reference specimen, however, these measurements should not be interpreted as an evaluation of absolute height accuracy. Nevertheless, SI and PWI recover comparable overall height distributions, with reconstructed height ranges consistent with those reported in previous topography measurements of comparable coins [26, 27].

An additional effect of SI is apparent in the height profile shown in Fig. 8(e). The slightly smoother height transition at the embossed edge is consistent with the

modified effective transfer function under SI, which can approach the response of an incoherent optical system [15, 16, 28].

Overall, SI introduces larger fluctuations for a single calibrated realization and therefore requires averaging over multiple statistically independent illumination patterns. However, once a sufficient number of realizations N is included, SI can reduce coherent artifacts below the corresponding PWI level. The selection of NA_{illu} and N therefore represents a trade-off between noise suppression, acquisition effort, sensitivity to spatial mismatches, and fidelity of the effective transfer function [17].

7.2 Axial Selectivity and Parasitic-Reflection Suppression

The experiments demonstrate that spatially diverse SI can substantially suppress parasitic reflections in DH. The axial-correlation measurements provide the physical basis for this effect. The correlation between speckle fields at axially separated planes decreases over a characteristic axial scale that can be approximated by the FWHM of the axial correlation function. Calibration using the mirror-reference field corresponding to the selected reconstruction plane therefore preserves the desired object contribution, whereas fields originating from sufficiently displaced interfaces become effectively decorrelated and are progressively attenuated by coherent averaging.

Figure 6 illustrates this behavior for the microscope-slide experiment. Under PWI, the rear-surface reflection interferes coherently with the desired front-surface reflection, producing a pronounced fringe pattern in both amplitude and phase. The substantially weaker artifacts in the IMAF-treated region confirm that the index-matching absorbing paste strongly attenuates the rear-surface reflection. However, the faint residual fringes observed in this region indicate that the attenuation is incomplete. A possible explanation is a residual refractive-index mismatch between the glass and the absorbing paste at the measurement wavelength, which may produce a weak reflection at the treated interface. Notably, calibration using a plane-wave mirror-reference measurement followed by averaging did not suppress the parasitic reflection because successive PWI acquisitions do not provide spatially diverse illumination. The parasitic interference pattern therefore remains correlated across acquisitions and is preserved by coherent averaging.

Under SI, the fringe artifacts decrease markedly with increasing NA_{illu} . This trend is consistent with the measured axial-correlation curves shown in Fig. 5. According to Eq. (13), the width of the central correlation peak scales inversely with the square of the illumination numerical aperture. Increasing the illumination numerical aperture therefore improves the axial discrimination between the front- and rear-surface contributions.

For $\text{NA}_{\text{illu}} = 0.02$, the measured correlation FWHM of 4.613 mm is substantially larger than the effective separation of the two slide surfaces, $\Delta z_{\text{g,eff}} \approx 1.47$ mm. The speckle fields at the two interfaces therefore remain strongly correlated, explaining the clearly visible residual fringes in Fig. 6(b) and (f). For $\text{NA}_{\text{illu}} = 0.08$, the axial correlation function is considerably narrower, and the rear-surface artifacts are almost completely suppressed. For $\text{NA}_{\text{illu}} = 0.04$, $\Delta z_{\text{g,eff}}$ also exceeds the measured FWHM of 1.174 mm. Nevertheless, Fig. 5(b) indicates that this separation lies near the first and

strongest side lobe of the measured correlation function. A non-negligible residual correlation may therefore remain, providing a plausible explanation for the weak fringes observed in the untreated region in Fig. 6(c) and (g). Thus, although the FWHM provides a useful estimate of the axial decorrelation length, the complete correlation function must be considered because its side lobes can retain residual correlations at larger axial separations.

This residual effect is visually discernible but difficult to quantify from the noise metrics alone. At $N = 100$, the amplitude and phase noise obtained with $\text{NA}_{\text{illu}} = 0.04$ are of the same order of magnitude as those obtained with $\text{NA}_{\text{illu}} = 0.08$. For both numerical apertures, the noise metrics initially decrease approximately according to the $1/\sqrt{N}$ dependence predicted by Eq. (22), as shown in Fig. 7, before approaching a residual noise floor. This behavior supports the interpretation that parasitic contributions from independent speckle realizations add with random relative phases.

The results in Fig. 8 demonstrate that the suppression mechanism also applies to rough, topographically structured surfaces. After insertion of the coverslip, the PWI reconstruction is dominated by interference artifacts and phase-unwrapping errors. In contrast, SI preserves the principal topographic features of the coin. The coverslip was positioned approximately 10 mm in front of the coin, corresponding to an effective round-trip axial separation of approximately 20 mm in air. This separation is substantially larger than the measured correlation FWHM of 1.174 mm for $\text{NA}_{\text{illu}} = 0.04$. The corresponding illumination fields are therefore only weakly correlated, allowing the coverslip reflections to be suppressed through calibration and coherent averaging.

Residual deviations remain near scratches and sharp topographic transitions. At these locations, the desired object field may be weak because of the local surface orientation, shadowing, or scattering outside the collection aperture. Speckle averaging can suppress decorrelated parasitic contributions, but it cannot recover a reliable phase if the desired object signal is weak relative to the parasitic and noise contributions. Such regions are therefore particularly susceptible to phase noise and incorrect ambiguity-order assignments during hierarchical multi-wavelength phase unwrapping. Amplitude-based masking could be used to identify unreliable pixels.

7.3 Numerical Refocusing and Extended-Range Reconstruction

The gauge-block experiment demonstrates that MWSIDH retains the numerical-refocusing capability of conventional DH while simultaneously suppressing axially displaced parasitic reflections. As shown in Fig. 9, the reconstructed complex fields were numerically propagated to the three block planes, which spanned a total axial range of 20.5 mm. At each reconstruction distance, the corresponding block was sharply resolved under both illumination modes. Under SI, the parasitic reflections introduced by the coverslip were additionally suppressed. The coverslip was positioned approximately 10 mm in front of the nearest gauge block, corresponding to an effective round-trip separation of approximately 20 mm in air. It was therefore separated from all block surfaces by substantially more than the measured correlation FWHM for $\text{NA}_{\text{illu}} = 0.04$. Consequently, the speckle fields associated with the coverslip and the selected block plane were only weakly correlated.

This result highlights an important distinction between MWSIDH and approaches based on temporally low-coherence illumination. A short temporal coherence length restricts interference to a narrow coherence gate and therefore typically requires mechanical scanning of the sample, objective, or reference path to measure surfaces extending over a large axial range [29, 30]. In MWSIDH, by contrast, the illumination remains temporally coherent, while effective axial selectivity is introduced numerically through the correlation properties of the spatially diverse speckle fields. The numerical-propagation capability of conventional DH is therefore retained without requiring mechanical axial scanning.

This axial selectivity also has an important consequence. Correct reconstruction at a selected axial position requires propagation of both the measured object fields and the corresponding mirror-reference fields to mutually matching planes before calibration and coherent averaging. At a given reconstruction distance, contributions originating from other axial planes are weakly correlated with the propagated mirror-reference field. Therefore, not only is the coverslip reflection suppressed, but contributions from the two blocks outside the selected reconstruction plane are also attenuated during coherent averaging. Because the block planes are separated by at least 10 mm, their speckle fields are effectively decorrelated from the corresponding reference field. Consequently, the out-of-focus contributions average toward zero as N increases.

In contrast, under PWI, all three blocks remain present at every reconstruction distance because no corresponding speckle-based axial discrimination occurs. However, two of the blocks are defocused, and all three are affected by parasitic interference. In the present implementation, the SI reconstructions were consequently processed separately for the three block planes, and the respective in-focus ROIs were combined afterward. A more general implementation could reconstruct a stack of axial planes and select the appropriate propagation distance for each pixel or local region using a suitable focus or correlation metric. Such an approach would permit automated reconstruction of specimens with continuously varying surface heights.

Once the three in-focus ROIs were combined, hierarchical multi-wavelength phase unwrapping recovered the complete axial arrangement of the blocks, as illustrated in Fig. 10. The total height variation of 20.5 mm lies within the unambiguous height range of approximately 38.6 mm provided by the longest synthetic wavelength, $\Lambda_{12} = 77.180$ mm. The successively shorter synthetic wavelengths then refined the height estimate to micrometer-scale precision. The reconstructed mean positions of the two outer blocks differ from their nominal values by only 2 μm and 1 μm , respectively, while the spatial standard deviations within the individual block ROIs ranged from approximately 1 μm to 2 μm . Under PWI, the substantially larger height variations result primarily from the parasitic interference introduced by the coverslip and the associated phase-unwrapping errors.

Overall, the gauge-block measurements demonstrate that MWSIDH combines numerical refocusing, suppression of axially displaced parasitic reflections, and hierarchical multi-wavelength phase unwrapping. Under SI, surfaces distributed over an axial range exceeding 20 mm can therefore be reconstructed with micrometer-scale

accuracy, provided that the fields associated with each surface are propagated to the appropriate axial plane before calibration and coherent averaging.

8 Conclusion and Outlook

In this work, MWSIDH was introduced and experimentally demonstrated as an effective approach for suppressing parasitic reflections in digital holography. The method exploits the finite axial correlation length of spatially diverse speckle fields, characterized by the FWHM of the axial correlation function. Calibration with the mirror-reference field associated with a selected reconstruction plane preserves the desired object contribution, whereas contributions originating from axially displaced interfaces are progressively attenuated during coherent averaging. Consequently, parasitic reflections can be suppressed without physically reducing the temporal coherence of the illumination while retaining the numerical-refocusing capability of digital holography.

The experimental results demonstrate that the method is applicable to planar interfaces as well as to rough and topographically structured specimens. In combination with hierarchical multi-wavelength phase unwrapping, MWSIDH further enables the reconstruction of axially separated surfaces over an extended axial range without mechanical axial scanning.

However, the method has several limitations. The axial selectivity that enables suppression of parasitic reflections attenuates not only unwanted reflections but also desired specimen contributions originating outside the selected reconstruction plane. Therefore, extended specimens with continuously varying topography cannot generally be reconstructed using a single global propagation distance. In addition, local regions with weak desired object signals, for example near steep surface slopes, shadowed areas, or pronounced surface defects, remain susceptible to residual phase noise and phase-unwrapping errors. Finally, the sequential acquisition of phase-shifted holograms across multiple wavelengths and speckle realizations leads to a substantial data volume and prolonged acquisition times. For an experiment involving eight wavelengths, 100 diffuser positions, and four-step phase shifting, a single specimen measurement requires 3200 interferograms. Although the corresponding mirror-reference holograms and reference-beam intensity recordings only need to be acquired once for a stationary setup, the total measurement time currently restricts this implementation to static specimens.

Future work may address these limitations through automated axial selection and faster generation of reproducible illumination patterns. A pixel-wise or locally adaptive focusing framework that evaluates suitable focus or correlation metrics over a numerically propagated axial stack could select the appropriate reconstruction distance prior to calibration and coherent averaging. Such an approach would enable the automated reconstruction of specimens with unknown and continuously varying surface topography. In addition, programmable spatial light modulators (SLMs) or digital micromirror devices (DMDs) could replace the mechanically translated diffuser. These devices can generate statistically independent illumination patterns while allowing deterministic replay of the corresponding masks for specimen and mirror-reference

measurements. This would improve calibration reproducibility by reducing sensitivity to mechanical positioning errors and enable significantly faster acquisition schemes. Finally, multiplexed off-axis DH could remove the need for the four-step phase-shifting sequence [31, 32]. If two wavelengths were recorded simultaneously using separable spatial carrier frequencies, all eight wavelengths could be acquired in four holograms per diffuser position. For 100 diffuser positions, this would reduce the specimen acquisition from 3200 phase-shifted interferograms to 400 off-axis holograms, provided that the multiplexed spectral components can be separated without overlap. However, this speedup comes at the cost of a reduced usable space-bandwidth product, since the available bandwidth must be shared among the multiplexed components to avoid spectral cross-talk.

Overall, MWSIDH provides a flexible framework for combining parasitic-reflection suppression, numerical refocusing, and extended-range multi-wavelength topography reconstruction. This makes the approach promising for non-contact three-dimensional surface metrology in optical configurations where parasitic reflections would otherwise limit the reliability of coherent measurements.

Acknowledgements. The authors express their gratitude to Peter Bonanati, Paul Fuchs, Wang-Cheng Yen and Arya Sankar for their support and valuable contributions throughout this research.

Declarations

Funding

The authors received no specific funding for this work.

Conflict of interest

The authors declare no conflict of interest.

Ethics approval and consent for publication

Not applicable.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Materials availability

Not applicable.

Code availability

Not applicable.

Author contributions

Antonius Schiebelbein performed the experiments, developed the data-processing workflow, analyzed the data, developed the methodology and drafted the manuscript. Tobias Schmitt-Manderbach, Daniel Bublitz, and Dirk Seidel contributed to the experimental concept, methodology, and interpretation of the results. Giancarlo Pedrini and Stephan Reichelt contributed to supervision, methodology, and interpretation of the results. All authors reviewed and approved the final manuscript.

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