

Article

Fourier-Based Characterization of Reflective Surface Topography Using a Heterodyne Optical Profilometer

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Abstract

Optical profilometry based on heterodyne interferometry was used to characterize the lateral surface topography of reflective surfaces with microstructures. A 633 nm laser beam is split into an unshifted object beam and a reference beam that is frequency-shifted by 80 MHz using a traveling-wave acousto-optic modulator. The object beam is focused onto the sample through a 100× microscope objective, recombined with the reference beam, and detected using a photodetector with a bandwidth of 150 MHz. At each scan position, a Universal Software Radio Peripheral (USRP) acquires the beat signal, and Fourier analysis isolates the heterodyne component. Electrical tests verified the recovery of a prescribed low-amplitude modulation, whereas translation of a plane mirror through focus identified a monotonic region for displacement-sensitive operation. Reflective silicon microstructures and a nominal 300 lines mm^{−1} grating were examined. The reconstructed maps reproduced the principal lateral features observed by scanning electron microscopy (SEM). For the grating-period comparison, the SEM-derived mean was 3.545 μm, whereas the heterodyne reconstruction yielded a representative period of approximately 3.50 μm, corresponding to an absolute difference of approximately 0.045 μm (1.3%). The present experiments establish Fourier-domain signal recovery and lateral morphological characterization. Because a traceable axial calibration and an uncertainty budget were not available, the reconstructed vertical coordinate remains qualitative, and the results do not yet establish quantitative surface-roughness parameters.

Keywords: heterodyne interferometry; optical profilometry; Fourier analysis; surface topography; reflective surfaces; *USRP*; scanning electron microscopy



Received: 22 August 2026

Revised: 1 October 2026

Accepted: 7 October 2026

Published: 13 October 2026

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1. Introduction

Surface topography influences optical scattering, friction, adhesion, coating performance, and the functionality of microelectronic and precision-engineered components. Precise characterization is therefore relevant to microelectronics, microelectromechanical systems, optical manufacturing, and quality control. Contact stylus instruments remain important in surface-texture metrology [1]; however, the finite stylus radius and contact force may limit their use on delicate or highly structured samples. Optical methods provide a non-contact alternative and can recover dense surface information over a selected field [2,3].

Among optical techniques, interferometric profilometry is particularly useful because surface displacement is encoded in the phase of coherent fields. In reflection, a local displacement changes the round-trip optical path and therefore the detected phase [4,5]. Quantitative use of this relationship requires calibration, traceability, an explicit spatial-filtering procedure, and evaluation of measurement uncertainty [6–8]. These requirements are especially important when the intended measurand is surface roughness rather than only morphology or lateral feature size [9–11].

Heterodyne detection introduces a controlled frequency difference between the object and reference beams. Their superposition on a square-law detector produces a beat signal at the difference frequency, thereby moving the measurement band away from low-frequency intensity drift. The amplitude and phase of the beat component can then be isolated by synchronous or Fourier-domain processing. Fourier methods are well established in interferometric analysis [12–15], and heterodyne arrangements have previously been applied to small-profile and phase-object measurements [16–19].

The system considered here combines an 80 MHz acousto-optic frequency shift, point-by-point scanning through a microscope objective, and digital acquisition using a Universal Software Radio Peripheral (USRP). The study has three objectives: (i) to describe the propagation and heterodyne-detection model without altering the original theoretical development; (ii) to validate the electrical and optical acquisition chain; and (iii) to assess the correspondence between reconstructed maps and the principal lateral features observed by SEM. The experiments did not provide a traceable conversion of the recovered signal into absolute height. Accordingly, the work is presented as a characterization of reflective surface topography, and quantitative roughness parameters are reserved for a subsequent calibrated implementation [20].

2. Materials and Methods

2.1. Experimental Arrangement

The experimental arrangement is shown in Figure 1. A 633 nm, 5 mW polarized He–Ne laser (Thorlabs, HNL050L-EC), corresponding to an optical carrier frequency of approximately 473 THz, illuminates a traveling-wave acousto-optic modulator (AA Opto-Electronic, MT80-A1,5-VIS) operated at 80 MHz. The modulator introduces an 80 MHz frequency shift, producing the heterodyne beat detected by the photodetector. The zeroth-order beam and the frequency-shifted (+1) order are used as the object and reference beams, respectively, while the −1 order is blocked.

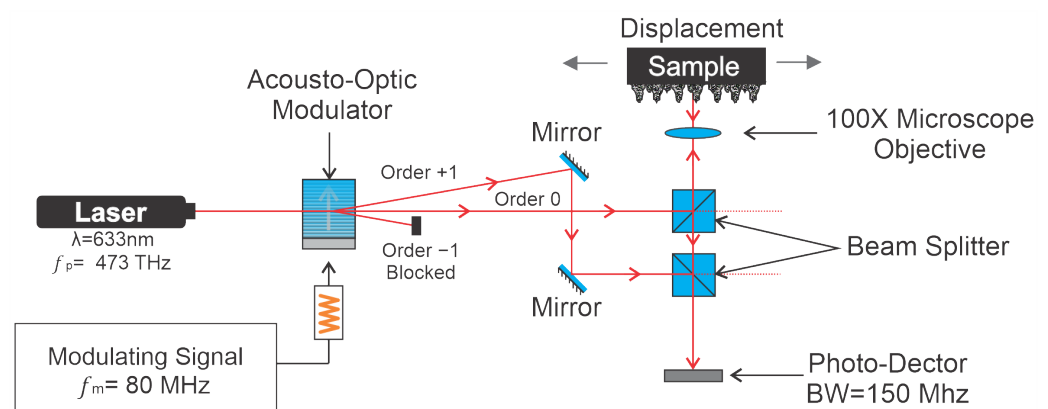


Figure 1. Optical arrangement of the heterodyne profilometer. The acousto-optic modulator generates the frequency-shifted and unshifted diffraction orders; the reflected object beam and the reference beam are recombined before photodetection.

The object beam is focused onto the sample through a 100 $\times$ oil-immersion microscope objective (Zeiss; NA = 1.25; working distance = 0.22 mm). The reflected object field is recombined with the reference field and detected by a high-speed photodetector (Thorlabs, DET10A; bandwidth 0–150 MHz). Thus, the 150 MHz value refers to the photodetector bandwidth and not to the optical carrier frequency. The resulting heterodyne signal is acquired using a Universal Software Radio Peripheral (National Instruments, USRP-2920).

For a wavelength of 633 nm and a numerical aperture of 1.25, the estimated Rayleigh lateral resolution is approximately 0.31 μm . Coarse positioning of the sample was performed using a motorized linear stage (Zaber, LSQ300B). Fine two-dimensional raster scanning was performed using a piezoelectric flexure stage (Thorlabs, MAX302).

The USRP receiver was configured with a center frequency of 80 MHz, an IQ sampling rate of 200 kS/s, a receiver gain of 10 dB, and the RX1 input port. The USRP-2920 has a specified receiver tuning range of 50 MHz to 2.2 GHz. The selected 80 MHz heterodyne frequency lies within the reported 0–150 MHz bandwidth of the photodetector while providing sufficient margin above the lower tuning limit of the receiver.

For a reflecting surface, a local height change produces a round-trip optical-path variation. After reference-phase subtraction and phase unwrapping, the ideal phase-to-height relation is

$$h(x, y) = \frac{\lambda \Delta\phi(x, y)}{4\pi}, \quad (1)$$

where λ is the optical wavelength and $\Delta\phi$ is the surface-dependent phase change. Equation (1) provides the theoretical conversion; it is not used below to claim absolute height because the experimental axial response was not traceably calibrated.

2.2. Propagation Model

The theoretical model follows the coherent propagation of a Gaussian object beam through the microscope objective O , reflection at the sample S , and return propagation to the lens plane A , as shown in Figure 2. Let (x, y) denote coordinates in the objective or detector plane, as specified by the context, and let (ξ, η) denote coordinates in the sample plane. A time-independent, ideally nondivergent (plane wavefront) incident Gaussian field is represented by

$$E_i(x, y) = E_0 \exp\left[-\frac{x^2 + y^2}{w_0^2}\right], \quad (2)$$

where E_0 is the complex electric field amplitude on the axis and w_0 is the Gaussian beam radius. The beam radius was not independently measured during the experimental implementation. A nominal value of $w_0 = 0.405$ mm, derived from the manufacturer's specified $1/e^2$ beam diameter of 0.81 mm, was therefore used as a parameter of the Gaussian propagation model. Treating the microscope objective O as a thin lens with pupil function $P(x, y)$ and focal length f , the transmitted field just after it is

$$E'_i(x, y) = E_0 \exp\left[-\frac{x^2 + y^2}{w_0^2}\right] P(x, y) \exp\left[-i\frac{k}{2f}(x^2 + y^2)\right]. \quad (3)$$

The Fresnel diffraction integral is evaluated over the propagation distance $f + h(\xi, \eta)$, where $h(\xi, \eta)$ is the height of the local irregularity on the surface S with respect to the nominal focal plane B . Thus,

$$E_S(\xi, \eta) = \frac{E_0 \exp\{ik[f + h(\xi, \eta)]\}}{i\lambda f} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} P(x, y) \exp\left[-\frac{x^2 + y^2}{w_0^2}\right] \exp\left[-i\frac{k}{2f}(x^2 + y^2)\right] \\ \times \exp\left\{i\frac{k}{2[f + h(\xi, \eta)]}[(x - \xi)^2 + (y - \eta)^2]\right\} dx dy, \quad (4)$$

where the inverse distance factor affecting the field amplitude can be approximated by f assuming that surface irregularities are small relative to the focal length, while the phase terms are retained. Equation (4) can be rewritten as

$$E_S(\xi, \eta) = \frac{E_0 \exp\left\{ikf\left[1 + \frac{h(\xi, \eta)}{f}\right]\right\} \exp\left\{i\frac{k}{2f}\left[1 + \frac{h(\xi, \eta)}{f}\right]^{-1}(\xi^2 + \eta^2)\right\}}{i\lambda f} \times \mathcal{F}\left\{P(x, y) \exp\left[-\frac{x^2 + y^2}{W^2(\xi, \eta)}\right]\right\}. \quad (5)$$

where $\mathcal{F}\{\cdot\}$ denotes the Fourier-transform operator and $W(\xi, \eta)$ is the actual Gaussian beam radius of a divergent/convergent beam wavefront, which is defined as

$$W^2(\xi, \eta) = \frac{2fw_0^2[f + h(\xi, \eta)]}{2f[f + h(\xi, \eta)] + ikw_0^2h(\xi, \eta)}. \quad (6)$$

The components of the spatial frequency spectrum are now given as $\nu_\xi = \xi/\lambda[f + h(\xi, \eta)]$ and $\nu_\eta = \eta/\lambda[f + h(\xi, \eta)]$.

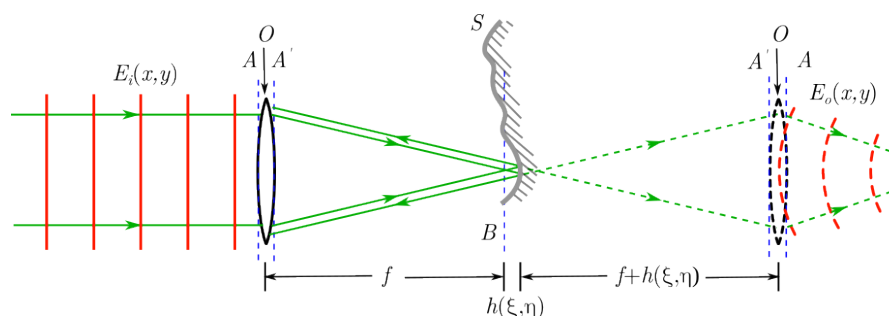


Figure 2. Schematic to determine the phase shift introduced by the local irregularity height in the probe Gaussian beam.

After reflection, the field propagates backwards along the incident path to the plane A' . A second application of the Fresnel integral gives

$$E'_o(x, y) = \frac{\exp\left\{ikf\left[1 + \frac{h(\xi, \eta)}{f}\right]\right\}}{i\lambda f} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} E_S(\xi, \eta) \times \exp\left\{i\frac{k}{2f}\left[1 + \frac{h(\xi, \eta)}{f}\right]^{-1}[(\xi - x)^2 + (\eta - y)^2]\right\} d\xi d\eta. \quad (7)$$

At this point, let us assume that the angular spectrum is collected completely by the lens, namely, $P(x, y) = 1$. Then, after a little algebraic effort, the returned field can be expressed as

$$E'_o(x, y) = \frac{\pi^2 E_0 W^2(\xi, \eta) W'^2(\xi, \eta)}{\lambda^2 f^2} \exp\left\{i2kf\left[1 + \frac{h(\xi, \eta)}{f}\right]\right\} \exp\left[-\frac{x^2 + y^2}{W_o^2(\xi, \eta)}\right], \quad (8)$$

where

$$W'^2(\xi, \eta) = \frac{4[f + h(\xi, \eta)]^2}{i4k[f + h(\xi, \eta)] - k^2 W^2(\xi, \eta)}, \quad (9)$$

and

$$W_o^2(\xi, \eta) = \frac{i4[f + h(\xi, \eta)]^2 - kW^2(\xi, \eta)[f + h(\xi, \eta)]}{ik^2 W^2(\xi, \eta) + 2k[f + h(\xi, \eta)]}. \quad (10)$$

The real part of $W_o^{-2}(\xi, \eta)$ is related to the squared Gaussian beam radius $w^2(\xi, \eta)$ and the imaginary one to the wavefront curvature $R(\xi, \eta)$. Thus,

$$w^2(\xi, \eta) = \frac{k^2 W^4(\xi, \eta) [f + h(\xi, \eta)]^2 + 16 [f + h(\xi, \eta)]^4}{2k^2 W^2(\xi, \eta) [f + h(\xi, \eta)]^2}, \quad (11)$$

and

$$2R(\xi, \eta) = -\frac{k^2 W^4(\xi, \eta) [f + h(\xi, \eta)]^2 + 16 [f + h(\xi, \eta)]^4}{8 [f + h(\xi, \eta)]^3 + k^2 [f + h(\xi, \eta)] W^4(\xi, \eta)}. \quad (12)$$

Including the phase transformation introduced by the objective lens on return and the temporal dependence of the object beam yields, using Equations (11) and (12),

$$E_o(x, y; t) = \frac{\pi^2 E_0 W^2(\xi, \eta) W'^2(\xi, \eta)}{\lambda^2 f^2} \exp \left\{ i2kf \left[1 + \frac{h(\xi, \eta)}{f} \right] \right\} \\ \times \exp \left[-\frac{x^2 + y^2}{w^2(\xi, \eta)} \right] \exp \left\{ -\frac{ik}{2} \left[\frac{1}{R(\xi, \eta)} + \frac{1}{f} \right] (x^2 + y^2) \right\} \exp(-i\omega t). \quad (13)$$

The reference beam is represented by an ideal Gaussian field with plane wavefront and shifted angular frequency ω_s :

$$E_R(x, y; t) = E_0 \exp \left[-\frac{x^2 + y^2}{2w_0^2} \right] \exp(-i\omega_s t). \quad (14)$$

2.3. Heterodyne Irradiance and Corrected Phase Convention

The superposition of the object and reference beams at the detector produces the irradiance

$$I(x, y, t) = I_1(x, y) + I_2(x, y) + 2\sqrt{I_1(x, y)I_2(x, y)} \cos[\Delta\phi(x, y, t)], \quad (15)$$

where the object-beam irradiance is

$$I_1(x, y) = \left| \frac{\pi^2 E_0 W^2(\xi, \eta) W'^2(\xi, \eta)}{\lambda^2 f^2} \right|^2 \exp \left[-\frac{2(x^2 + y^2)}{w^2(\xi, \eta)} \right], \quad (16)$$

and the reference-beam irradiance is

$$I_2(x, y) = |E_0|^2 \exp \left[-\frac{2(x^2 + y^2)}{w_0^2} \right]. \quad (17)$$

To make the temporal convention explicit, define the heterodyne angular frequency as $\Delta\omega = \omega_s - \omega$. Taking the object phase relative to the reference phase, the phase difference is

$$\Delta\phi(x, y, t) = 2kf \left[1 + \frac{h(\xi, \eta)}{f} \right] - \frac{k}{2} \left[\frac{1}{R(\xi, \eta)} + \frac{1}{f} \right] (x^2 + y^2) + \Delta\omega t. \quad (18)$$

In the experimental implementation, the heterodyne frequency difference was $\Delta f = 80$ MHz, corresponding to $\Delta\omega = 2\pi\Delta f \approx 5.03 \times 10^8$ rad/s. Only this heterodyne frequency was evaluated experimentally; no frequency optimization or sweep was performed.

Substitution of Equations (16) and (17) into Equation (15) gives the corrected explicit detector irradiance:

$$I(x, y, t) = \left| \frac{\pi^2 E_0 W^2(\xi, \eta) W'^2(\xi, \eta)}{\lambda^2 f^2} \right|^2 \exp \left[-\frac{2(x^2 + y^2)}{w^2(\xi, \eta)} \right] + |E_0|^2 \exp \left[-\frac{2(x^2 + y^2)}{w_0^2} \right] \\ + 2 \left| \frac{\pi^2 W^2(\xi, \eta) W'^2(\xi, \eta)}{\lambda^2 f^2} \right| |E_0|^2 \exp \left\{ -\left[\frac{1}{w^2(\xi, \eta)} + \frac{1}{w_0^2} \right] (x^2 + y^2) \right\} \cos[\Delta\phi(x, y, t)]. \quad (19)$$

Equation (19) contains two slowly varying background terms and a time-dependent heterodyne cross term. The latter contains the surface information and has an amplitude proportional to the geometric mean of the object- and reference-beam irradiances. Its amplitude consequently depends on the spatial overlap, relative optical power, sample reflectivity, and local slope.

For a reflective surface, the dominant height-dependent phase contribution is $2kh = 4\pi h/\lambda$, because the optical field traverses the displacement twice. The quadratic term proportional to $x^2 + y^2$ accounts for wavefront curvature and defocus. Under the condition $|h| \ll f$, the phase response may dominate over changes in the propagation amplitude factors, but this approximation does not eliminate the need to calibrate reflectivity and defocus effects. The experimental evaluation below therefore uses the reconstructed vertical coordinate qualitatively.

Table 1. Nomenclature used in Equations (1)–(19).

Symbol	Definition
(x, y)	Coordinates in the objective or detector plane; in Equation (1), lateral coordinates of the reconstructed map.
(ξ, η)	Coordinates in the sample plane.
E_0	On-axis complex field amplitude under the equal-input-amplitude assumption.
E_i, E'_i	Incident field before and immediately after the microscope objective.
E_o, E'_o	Backpropagation fields in front and behind the microscope objective.
$P(x, y)$	Objective pupil function.
w_0	Gaussian beam radius used in the field model.
f	Effective focal length of the microscope objective.
$h(\xi, \eta)$	Local sample displacement relative to the nominal focal plane.
$k = 2\pi/\lambda$	Optical wavenumber.
ω, ω_s	Object- and frequency-shifted reference-beam angular frequencies.
$\Delta\omega = \omega_s - \omega$	Heterodyne beat angular frequency.
W, W_o	Gaussian beam radius at different propagation stages.
I_1, I_2, I	Object-beam, reference-beam, and total detector irradiance.
$\Delta\phi$	Object-to-reference phase difference under the convention used in Equation (18).

2.4. Experimental Evaluation and Reference Samples

The assessment was organized in three stages. First, a prescribed low-amplitude signal was generated and recovered using two USRP devices to evaluate the acquisition and processing chain independently of the optics. Second, the optical detector signal was examined in the frequency domain to identify the component associated with the 80 MHz shift. Third, a plane mirror was translated through the objective focus to identify a monotonic working region, after which structured reflective samples were raster scanned.

The samples consisted of silicon integrated-circuit microstructures and a reflective grating with a nominal spatial frequency of 300 lines mm^{-1} . SEM acquisition parameters were extracted from the metadata files generated by the microscope for each micrograph. The SEM images were acquired using a scanning electron microscope (JEOL JSM-7800F, JEOL Ltd., Tokyo, Japan). The silicon microstructure shown in Figure 4 was imaged at an accelerating voltage of 10.0 kV, a magnification of 12000 $\times$, and a working distance of 8.9 mm, with a 1 μm scale bar. A second micrograph of the same silicon sample, used for the lateral dimensional comparison in Figure 8,

was acquired at 1.0 kV, 1400 $\times$ magnification, and a working distance of 9.87 mm, with a 10 μ m scale bar. The reflective grating micrograph used for the lateral-period comparison in Figure 9 was acquired with the same instrument at 15.0 kV, 8000 $\times$ magnification, and a working distance of 10.14 mm, with a 1 μ m scale bar.

Two period values annotated in the original grating micrograph were 3.52 and 3.57 μ m, giving a mean period of 3.545 μ m. The SEM images served as references for morphological assessment and lateral dimensional comparison. However, because the available data do not provide a traceable lateral calibration uncertainty or a calibrated three-dimensional reconstruction, they were not considered traceable reference measurements for lateral dimensions, surface height, or roughness.

At each raster position, three consecutive records of 1000 complex I/Q samples were acquired at an IQ sampling rate of 200 kS/s. Each record was processed in LabVIEW using FFT-based spectral analysis. The dominant heterodyne spectral component was identified, and a narrow spectral interval around the peak was numerically integrated. The three resulting values were averaged to obtain the measurement associated with each raster position. No additional digital band-pass filter was applied in the LabVIEW processing. Spectral selection was instead performed in the Fourier domain by identifying the dominant heterodyne component and numerically integrating a narrow spectral interval around its peak.

3. Results

3.1. Electrical Validation of the Processing Chain

An 80 MHz carrier with an amplitude of 1 V_{pp} was generated by the first USRP and amplitude modulated by a random waveform ranging from 0 to 0.5 mV_{pp}. A second USRP acquired the modulated carrier, and the received complex I/Q data were processed in LabVIEW using FFT-based spectral analysis. The dominant spectral component was identified, a narrow spectral interval around the peak was numerically integrated, and repeated acquisitions were averaged to recover the imposed low-frequency amplitude variations.

Figure 3 compares the programmed and recovered waveforms. Their temporal patterns are qualitatively consistent, although the recovered waveform exhibits residual high-frequency fluctuations that were not fully suppressed by the spectral-extraction and averaging procedure. These fluctuations may arise from electronic noise, finite-record effects associated with the acquisition window, and point-to-point variations in the estimated spectral amplitude following FFT-based spectral extraction. A numerical recovery error cannot be reported without the original synchronized arrays.

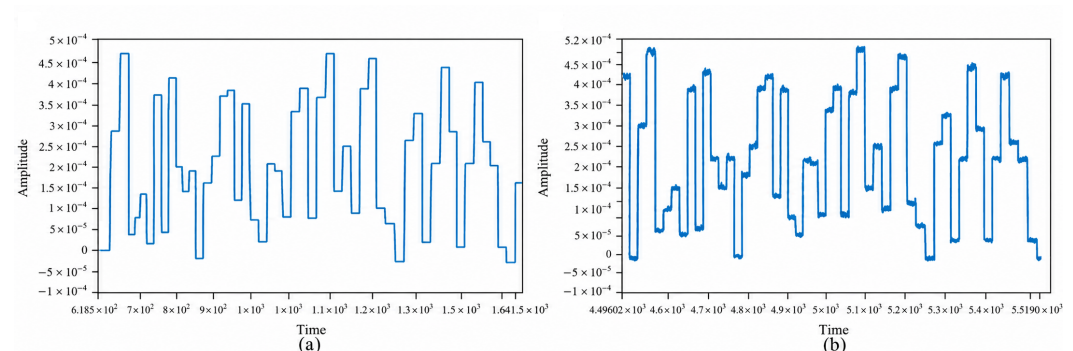


Figure 3. Electrical validation of the USRP processing chain: (a) prescribed low-amplitude random modulation; (b) modulation recovered after FFT-based spectral extraction, numerical integration, and averaging.

3.2. Optical Beat Detection and Operating-Point Selection

After electrical validation, the optical heterodyne signal detected by the DET10A photodetector was acquired using the USRP. Figure 4 shows the measured spectrum after tuning the receiver around the heterodyne carrier frequency. The dominant spectral component corresponds to the 80 MHz optical frequency difference. Because the NI USRP-2920 was tuned to 80 MHz, the received signal was downconverted to complex baseband I/Q data prior to digital processing. Consequently, the horizontal axis is expressed as frequency offset relative to the tuned carrier rather than as an absolute radio-frequency spectrum. Secondary spectral components are also observed around the dominant heterodyne component.

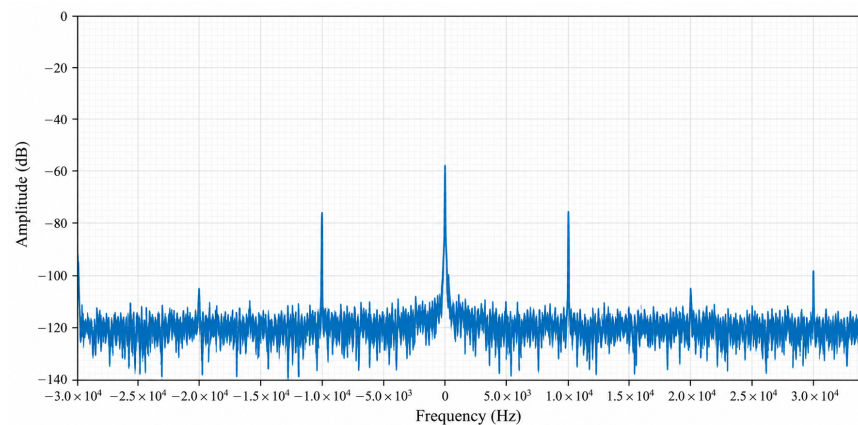


Figure 4. Representative detector spectrum displayed as frequency offset from the 80 MHz tuned carrier. The central component is the heterodyne beat used for demodulation.

A plane mirror was positioned near the objective focus and translated axially in the experimental system. Figure 5 compares the axial response predicted by the theoretical model with the experimentally measured response of the present system. In both cases, the collected signal exhibits a non-monotonic dependence on axial position. A region with a pronounced monotonic slope was selected as the operating region because it provides higher displacement sensitivity. The experimental measurement supports this operating-point selection, but it does not by itself provide a traceable axial calibration because the slope, valid range, repeatability, and uncertainty were not established from a calibrated displacement standard.

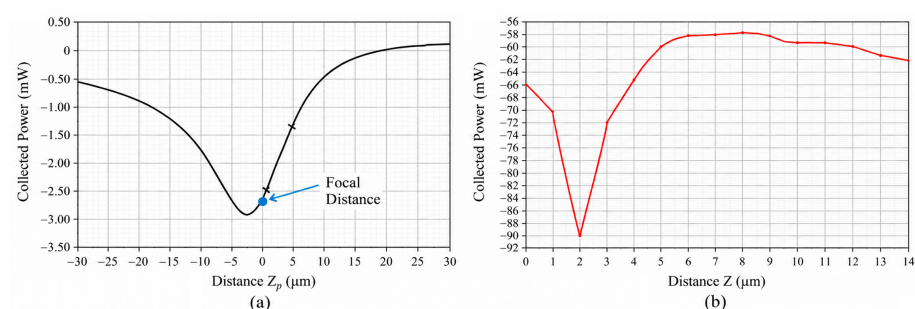


Figure 5. Axial response around the objective focus: (a) theoretical collected-power response calculated as a function of defocusing distance; (b) experimentally measured response of the present heterodyne system obtained by translating a plane mirror axially. A monotonic region of the response was used for operating-point selection.

3.3. Reflective Silicon Microstructures

The silicon sample was examined by SEM and scanned with the heterodyne profilometer. Figure 6 compares a junction between four structures. Both images reproduce the same

principal lateral organization, including the central intersection and the adjacent edges. The heterodyne map also shows intensity variations within nominally similar regions; these variations may contain contributions from height, reflectivity, speckle, local slope, and optical alignment and should not be attributed exclusively to surface height.

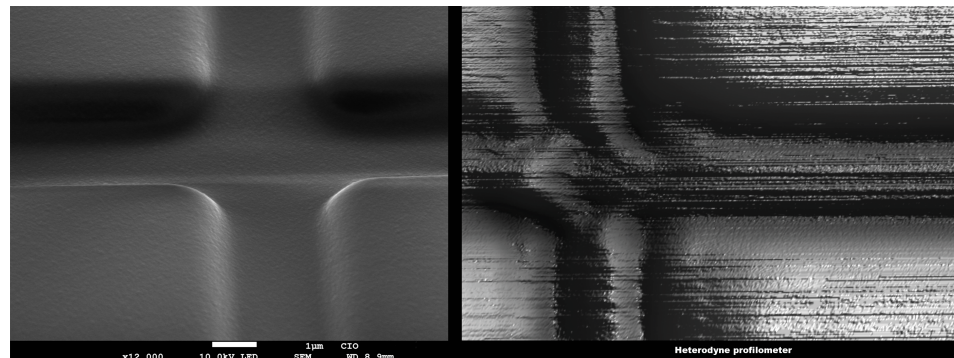


Figure 6. Representative silicon microstructure observed by SEM (left) and reconstructed with the heterodyne profilometer (right). The comparison establishes morphological correspondence in the lateral plane; the vertical scales are not traceably linked.

Representative profiles and three-dimensional renderings are shown in Figure 7. The central depression and surrounding elevated structures are present in both data representations. Differences in the detailed profile shapes are expected because the instruments use different interaction mechanisms and because the profilometer response has not been separated from local reflectivity and defocus. The three-dimensional views are therefore used to display morphology, not to report absolute height.

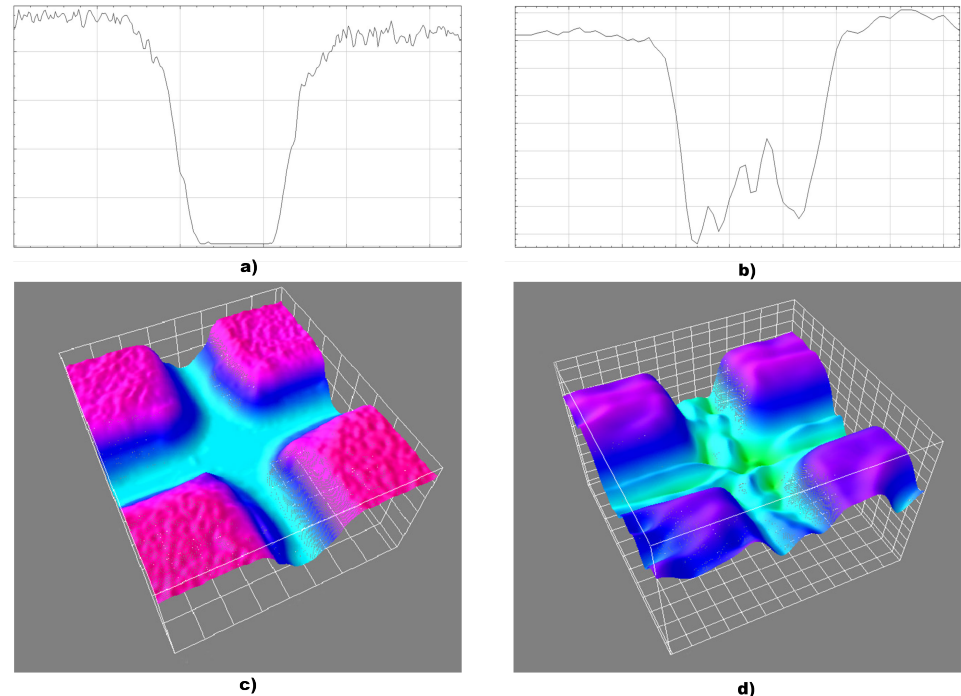


Figure 7. Representative silicon results: (a) profile obtained from the SEM-related image processing; (b) heterodyne profile; (c) SEM-related three-dimensional rendering; and (d) heterodyne reconstruction. Vertical values are shown in the original arbitrary or uncalibrated scales. The colors are used solely to enhance the visualization of relative variations in the reconstructed surface profile. They do not correspond to a calibrated vertical scale and should not be interpreted as quantitative measurements of surface height or depth.

3.4. Lateral Dimensional Comparison

For the representative silicon feature in Figure 8, the heterodyne profile indicates a width of 19.6 μm , whereas the SEM annotation gives 19.86 μm .

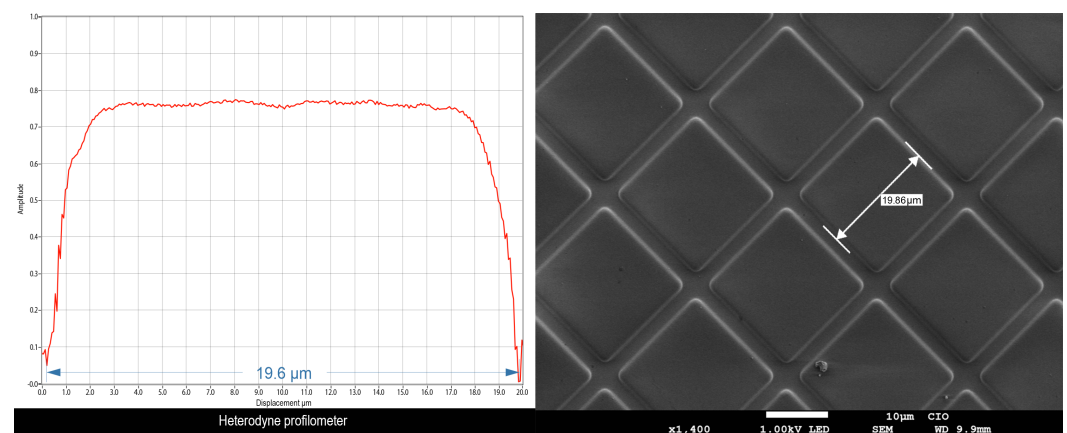


Figure 8. Lateral dimension of a representative silicon feature obtained from the heterodyne profile (left, 19.6 μm) and SEM image (right, 19.86 μm).

The absolute difference is therefore 0.26 μm , corresponding to approximately 1.3%. This is a single lateral dimensional comparison; repetitions and an uncertainty estimate are required before the value can be generalized as an instrument error.

The nominal 300 lines mm^{-1} grating has a calculated pitch of 3.333 μm . In the available SEM image, the two annotated periods are approximately 3.52 and 3.57 μm , yielding a mean value of 3.545 μm (approximately 3.55 μm). The heterodyne reconstruction shows a representative period of approximately 3.50 μm (Figure 9). Based on these available values, the absolute difference between the SEM-derived mean and the heterodyne result is approximately 0.045 μm , corresponding to about 1.3%. This comparison is limited to the available lateral measurements and should not be interpreted as a general specification of instrument accuracy.

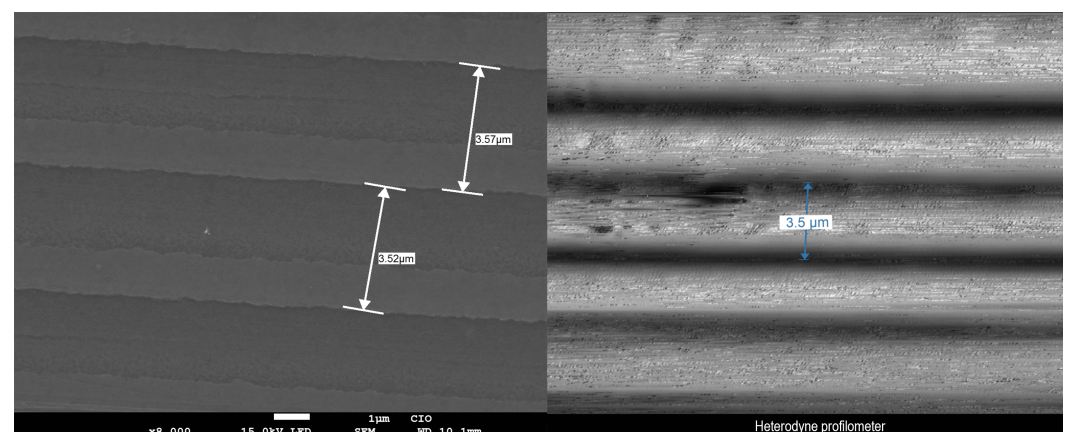


Figure 9. Lateral-period comparison for the nominal 300 lines mm^{-1} reflective grating: SEM annotations (left) and heterodyne reconstruction (right).

Figure 10 collects the corresponding profiles and surface renderings. The periodic structure is reproduced by both approaches. The heterodyne reconstruction exhibits a more regular periodic pattern, whereas the SEM-related reconstruction contains greater local variation. Since the vertical coordinates were not calibrated to a common scale, the comparison is restricted to periodicity and morphology.

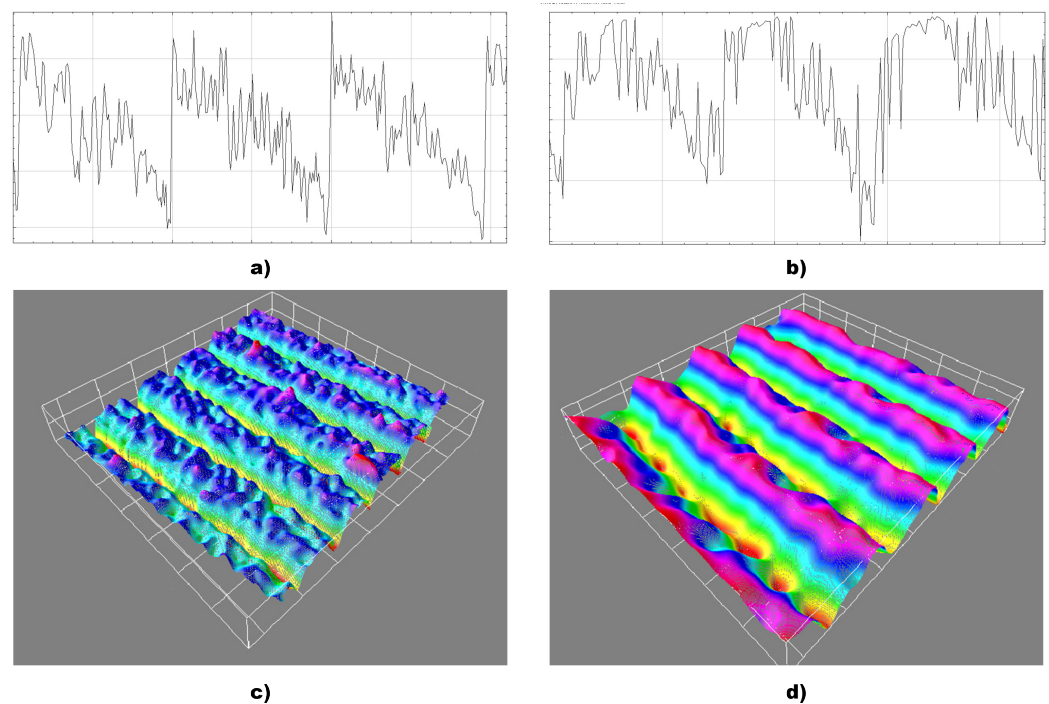


Figure 10. Representative grating results: (a) SEM-related profile; (b) heterodyne profile; (c) SEM-related surface rendering; and (d) heterodyne surface reconstruction. The comparison is limited to lateral periodicity and morphology. The color maps provide a qualitative visualization of relative variations in the reconstructed grating profile. The colors do not represent calibrated height or depth values, and no quantitative vertical scale is provided.

3.5. Sampling Density and Acquisition Time

The lateral sampling density can be adjusted without modifying the optical arrangement. For the acquisition parameters used in this work, each raster position was measured using three consecutive records of 1000 complex I/Q samples acquired at an IQ sampling rate of 200 kS/s. Each record corresponded to an acquisition interval of 5 ms, yielding a minimum signal-acquisition time of approximately 15 ms per measurement point. A 1200×1200 raster contains 1.44×10^6 points. At 15 ms per point, the theoretical minimum acquisition time is 21,600 s (6 h), excluding stage settling, communication, and processing overhead. These estimates illustrate the direct trade-off between lateral sampling density and total acquisition time.

$$t_{\text{scan}} = (1200)^2(15 \text{ ms}) = 21600 \text{ s} = 6 \text{ h}. \quad (20)$$

4. Discussion

The experiments establish three capabilities of the system. First, the USRP-based acquisition chain isolates an 80 MHz carrier and recovers a prescribed modulation. Second, the optical arrangement produces a displacement-sensitive response around the microscope-objective focus. Third, raster scanning reconstructs the principal lateral morphology of reflective silicon and grating samples. The approximately 1.3% difference obtained from the available grating-period measurements is a lateral dimensional comparison and should not be interpreted as a surface-roughness error or as a general specification of instrument accuracy.

The principal metrological limitation is the absence of a traceable vertical calibration. Surface roughness is calculated from a height distribution after specified form removal and spatial filtering; it cannot be inferred solely from visual image correspondence, intensity contrast, or lateral periodicity. In the present amplitude-sensitive implementation, reflectiv-

ity, local surface slope, speckle, the objective transfer function, polarization, and alignment may all change the recovered heterodyne amplitude. These influence quantities must either be separated from the height response or incorporated into a calibrated measurement model and uncertainty budget [21–23].

The SEM comparisons provide useful evidence of feature localization and lateral dimensional agreement, but they also require careful interpretation. A conventional single-view SEM image does not directly provide traceable surface height. A rigorous inter-instrument comparison should register the same region, define the measurand identically, state the SEM dimensional calibration, repeat both measurements at several locations, and compare mean values together with their associated uncertainties. The difference between the nominal grating pitch of $3.333\text{ }\mu\text{m}$ and the reported SEM-derived mean of $3.55\text{ }\mu\text{m}$ must also be resolved from the original dimensional records or the manufacturer's tolerance.

The next metrological step is to measure one or more certified step-height or roughness artifacts over the intended axial range. Repeated forward and reverse mirror sweeps would permit estimation of sensitivity, nonlinearity, hysteresis, repeatability, and drift. Once the vertical scale is established, the surface should be leveled, form and waviness should be removed using documented filters, and profile or areal parameters should be calculated following the applicable surface-texture standards. The point-scanning architecture is flexible, but its acquisition time scales directly with the number of raster points. Future work will therefore include optimization of the USRP acquisition parameters, including the IQ sampling rate, record length, and number of repeated acquisitions per raster position, with the objective of reducing acquisition time while preserving adequate spectral resolution and measurement stability. Faster stages, on-device demodulation, adaptive sampling, or parallel detection could provide additional improvements in throughput.

5. Conclusions

A scanning heterodyne optical profilometer incorporating an acousto-optic modulator, a high-speed silicon photodetector, and USRP-based Fourier-domain processing was evaluated for the non-contact characterization of reflective microstructured surfaces. The heterodyne component associated with the 80 MHz frequency shift was acquired and isolated, and two-dimensional mechanical scanning enabled reconstruction of surface profiles and morphological maps.

The electrical test showed qualitative recovery of a prescribed low-amplitude modulation. Silicon microstructures reconstructed by the profilometer reproduced the principal features observed by SEM. For a representative silicon feature, the lateral values were 19.6 and $19.86\text{ }\mu\text{m}$, giving an absolute difference of $0.26\text{ }\mu\text{m}$, corresponding to approximately 1.3%. For the nominal 300 lines mm^{-1} grating, the SEM-derived mean period was $3.545\text{ }\mu\text{m}$, whereas the heterodyne reconstruction yielded a representative period of approximately $3.50\text{ }\mu\text{m}$, corresponding to an absolute difference of approximately $0.045\text{ }\mu\text{m}$ (1.3%). Under the acquisition parameters used in this work, the minimum signal-acquisition time was approximately 15 ms per raster point, corresponding to about 6 h for a 1200×1200 scan, before accounting for stage-settling, communication, and processing overhead.

The present implementation provides quantitative information in the lateral plane and qualitative information regarding axial morphology. A traceable conversion between the recovered heterodyne response and absolute surface height was not established. Consequently, the reconstructed vertical coordinate should not yet be interpreted as an absolute step-height or roughness measurement. Future work will focus on axial calibration using certified step-height or roughness artifacts, repeated measurements to evaluate repeatability and drift, development of an uncertainty budget, and implementation of documented spatial-filtering procedures. In addition, the USRP acquisition parameters, including the

I/Q sampling rate, record length, and number of repeated acquisitions at each raster point, will be optimized to reduce acquisition time while preserving spectral resolution and measurement stability. These developments are required before standardized quantitative roughness parameters can be reported and will extend the applicability of the system to metrological characterization of reflective microstructured surfaces.

Author Contributions: Conceptualization, G.M.-P. and G.G.-T.; Methodology, A.B.B.-G., G.M.-P., G.G.-T., and A.M.-N.; Validation, G.M.-P., G.G.-T., and A.M.-N.; Formal Analysis, A.B.B.-G., G.M.-P., G.G.-T., and A.M.-N.; Investigation, A.B.B.-G., G.M.-P., G.G.-T., and A.M.-N.; Resources, G.M.-P. and G.G.-T.; Data Curation, A.B.B.-G.; Writing—Original Draft, A.B.B.-G.; Writing—Review & Editing, G.M.-P., G.G.-T., and A.M.-N.; Visualization, A.B.B.-G., G.G.-T., and A.M.-N.; Supervision, G.M.-P. and G.G.-T.; Project Administration, G.G.-T.; Funding Acquisition, G.G.-T. All authors have read and agreed to the published version of the manuscript.

Funding: A.B.B.-G. acknowledges scholarship support from CONACyT (scholarship registration No. 249055).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available from the corresponding author upon reasonable request.

Acknowledgments: During the preparation of this manuscript, the authors used ChatGPT (GPT-5.6, OpenAI; accessed in July 2026) to assist with manuscript organization, language editing, and LaTeX formatting. The authors reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AOM	Acousto-optic modulator
FFT	Fast Fourier transform
SEM	Scanning electron microscopy
USRP	Universal Software Radio Peripheral

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