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Binary pseudo-random array test standard optimized for characterization of interferometric microscopes

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ABSTRACT

We describe a technique for measuring the instrument transfer function (ITF) of an interferometric microscope, allowing both characterization and data processing to increase the fidelity and effective resolution of the tool. The technique, based on test samples structured as two-dimensional (2D) binary pseudo-random arrays (BPRAs), employs the unique properties of the BPRA patterns in the spatial frequency domain. The inherent 2D power spectral density of the pattern has a deterministic white-noise-like character that allows direct determination of the ITF with uniform sensitivity over the entire spatial frequency range and field-of-view of an instrument. As such, the BPRA samples satisfy the characteristics of a test standard: functionality, ease of specification and fabrication, reproducibility, and low sensitivity to manufacturing error. We discuss the results of the development and application of highly randomized (HR) BPRA test samples with elementary feature sizes in the range from 80 nm and up to 2.5 µm, optimized for the ITF characterization of interferometric microscopes broadly used for 2D optical surface profiling. The data acquisition and analysis procedures for different applications of the ITF calibration technique developed are also discussed.

Keywords: calibration, instrument transfer function, power spectral density, interferometric microscopes, binary pseudo-random, test standard, aberration, surface metrology

1. INTRODUCTION

Confidence in the results provided by a metrology tool depends crucially on the ability to characterize or calibrate it. In addition, characterization can improve the performance of a metrology instrument by enabling data processing to mitigate the effects of its imperfections, resulting in an effective resolution beyond the nominal resolution of the tool (see, for example, Ref. [1] and references therein). However, there is no commonly accepted method to characterize the performance of metrology tools or calibrate them with high accuracy. Such characterization is a difficult task; the quality of the measured image data (topography) depends on both the tool itself and the experimental setup, and the interpretation of the results is often subjective and incomplete.

We are developing a robust methodology and technology, based on test samples structured as two-dimensional (2D) binary pseudo-random arrays (BPRAs) [2-10], to quantitatively characterize surface metrology instruments and create the first reliable and commercial solution for the beyond-resolution reconstruction of 2D surface topography data.

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The technology is intended to increase the accuracy and spatial resolution of the metrology data [11,12]. In particular, such high accuracy, high resolution data is needed for fabrication and optimal usage of the optical components in x-ray optical systems, and performance simulations of new x-ray space telescopes and x-ray beamlines under development.

Characterization of metrology systems requires artificial test patterns. The design of the artificial test patterns should correspond to the expected application of the results of the calibration such as determining the resolution, distortion, and spatial frequency response of the metrology system (for review, see, for example, Refs. [13,14]). The data obtained through calibration test target should help users better understand the imaging system so that a user can make an informed decision of upgrading or replacing the system and, more importantly, improve the recorded image using the calibration data. Existing calibration test samples do not allow this. Current test targets (such as the USAF 1951 resolution target, sign-wave modulation transfer function test patterns, and Spoke Resolution targets) have limited applications. Figure 1 illustrates the types of limitations that currently available calibration targets may have, including (Fig. 1a) characterization limited to only one spatial frequency (or a limited set of frequencies), or characterization only over a small area of the image (Fig. 1b), and not over the entire field of view. With such limited information, the characterization data cannot be used for improving images.

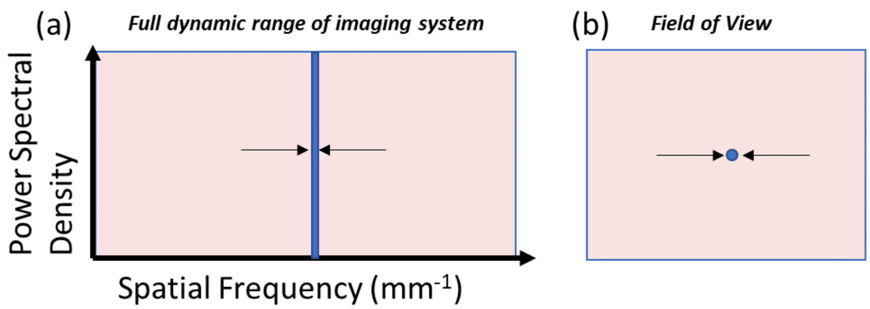

Figure 1. Illustration of the types of limitations of the current commercial calibration targets. (a) The calibration only provides information on the specific frequency and do not provide any information on full dynamic range of the imaging system. (b) Characterization is done only on the local spot of the image, and not for the entire field of view.

In this paper, we describe the development of a robust methodology and technology to quantitatively characterize surface metrology instrumentations and create the first reliable and commercial solution for the beyond-resolution reconstruction of 2D surface topography data. Our test samples consist of highly randomized (HR) binary pseudo random design and the software for data processing are described. Furthermore, we demonstrate, for the first time, image/data restoration using the analytical model of the instrument transfer function via measured calibration data, using a commercial test sample consisting of chirped gratings. We demonstrate that a factor of at least 3-4 times more information has been recovered through data reconstruction.

2. PRINCIPLE AND DESIGN OF HIGHLY RANDOMIZED BINARY PSEUDO-RANDOM PATTERNS

Even if measured (raw) images visually appear to be of a very high quality, from a metrological point of view the reliability of the measured data can suffer significantly from instrumental factors such as limited resolution, geometrical aberrations, drift, and noise, as well as from errors introduced by data processing and contrast enhancement algorithms used to preprocess the images. This necessitates high-accuracy and thorough characterization of the metrology tools. The instrument transfer function (ITF) that quantifies the instrument response to the various object structures as a function of the spatial frequency of the object topography [15], is one of the most comprehensive quantitative characteristics of metrological instruments. However, ITF characterization, especially in application to 2D metrology, is not widely used because the implementation is complex, and dedicated test samples with the required spatial frequencies have not been available.

Our ITF calibration method is based on measuring the spatial frequency response of the instrument from a specially designed test sample based on binary pseudo-random arrays [2-10]. Researchers from Lawrence Berkeley National Laboratory and Brookhaven National Laboratory originally suggested the use of binary pseudo random arrays to characterize the ITF of metrology systems [2]. The BPR samples come in various formats including 1D and 2D surface height patterns, and multilayers, as shown in Fig. 2(a).

The BPR test samples contain features with assigned fundamental (smallest feature) size at specific positions distributed over the test sample. It is pseudo-random since the exact positioning of its feature sizes are known by design. Randomness is mathematically deterministic and the algorithm for the improved highly randomized BPRA was recently developed and tested [10].

The key characteristics of the BPR test pattern is that power spectral density (PSD) distribution of such a sample is inherently flat, as shown in Fig. 2(b). The recorded deviation from the flat line (blue) provides the quantitative characterization of the ITF of the tool in use.

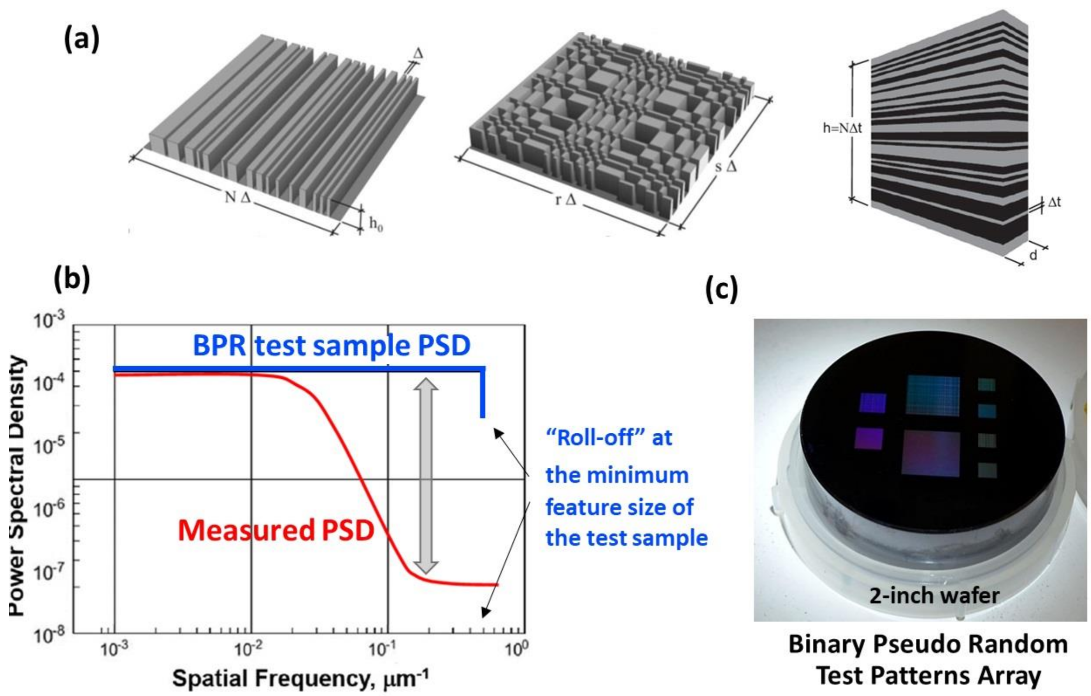

Figure 2. (a) from left: 1-D, 2-D binary pseudo-random surface height patterns, and multi-layers, (b) Power spectral density inherent to the BPRA (in blue), showing inherent flat line, and measured PSD (in red), which is convolved with the "signature" imperfections of the metrology tool. (c) A photograph of binary pseudo random test pattern array sample. The sample contains various fundamental sizes to cover a wide range of spatial frequencies.

In Fig. 2, we also show a BPRA sample containing test patterns with various fundamental sizes from 400 nm to 2.5 µm developed to cover a wide range of spatial frequencies accessible in surface topography measurements with interferometric microscopes.

The unique advantages of the BPRA samples are the following.

1) Power spectral density inherent to the BPRA test sample is constant (flat) over the entire usable spatial frequency range. PSD falls off only at the frequency of the fundamental feature size. This means that sensitivity to the ITF measurement is constant even at higher spatial frequencies.
2) The BPRA test-sample approach is applicable to a wide range of metrological instrumentations. Any binary physical properties that give image contrasts, for example: transmission, absorption, electron photo-emission, structure height, etc., can be used to create the corresponding BPRA test sample surface - Fig. 3.
3) System characterization via ITF can be done over the entire field of view, not just at a local area.
4) BPRA technology analytically and numerically characterizes the ITF of the imaging tools, which enables, for the first time, data-restoration using the quantitatively measured ITF (see Sec. 4).

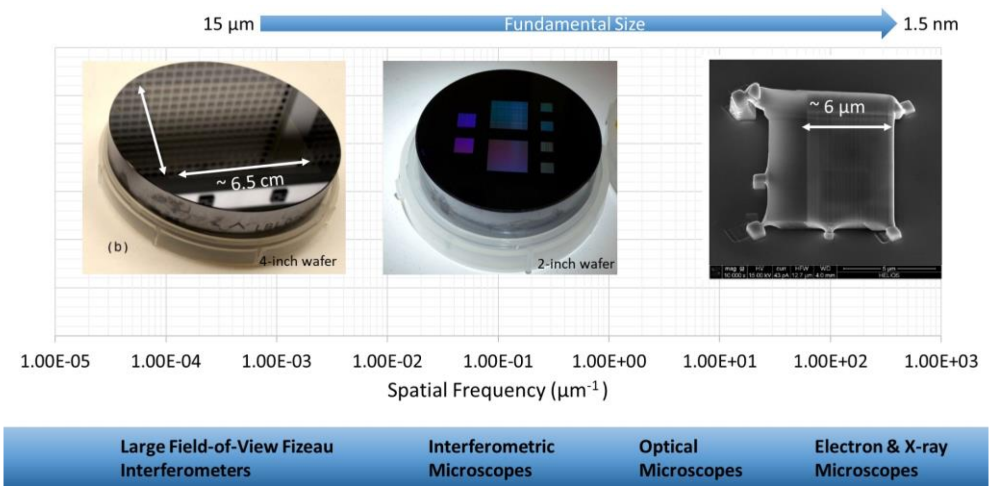

Figure 3. Several BPRA test samples designed, fabricated, and tested for a variety of metrology tools, including Fizeau interferometers, interferometric microscopes, and scanning probe and atomic force microscopes. The fundamental sizes of the arrays ranges from 1.5 nm to 15 µm.

3. APPLICATION OF BPR ARRAY IN METROLOGY OF X-RAY OPTICS

In this section, we describe the application of BPRA test samples in the metrology of X-ray optics at Lawrence Berkeley National Laboratory. The test samples were used for thorough characterization of the ITF of an interferometric microscope available at the Advanced Light Source (ALS) X-Ray Optics Laboratory (XROL) [16,17]. The photograph of the setup is shown in Fig. 4(a). In this example, a BPRA test pattern with 2.5 µm feature size with a total pattern area of about 10×10 mm^2 was used. The 64-exposition measurement was performed with a 2.75× objective with ×1.0 zoom lens which corresponds to 3.115 µm pixel size (resulting in a Nyquist frequency of ≈ 333 mm^{-1}). Figure 4(b) shows an image of the measured area of the BPRA test sample. The image depicts a white-noise-like character as expected, which allows for a direct determination of the ITF with a uniform sensitivity over the entire spatial frequency range and field of view of an instrument.

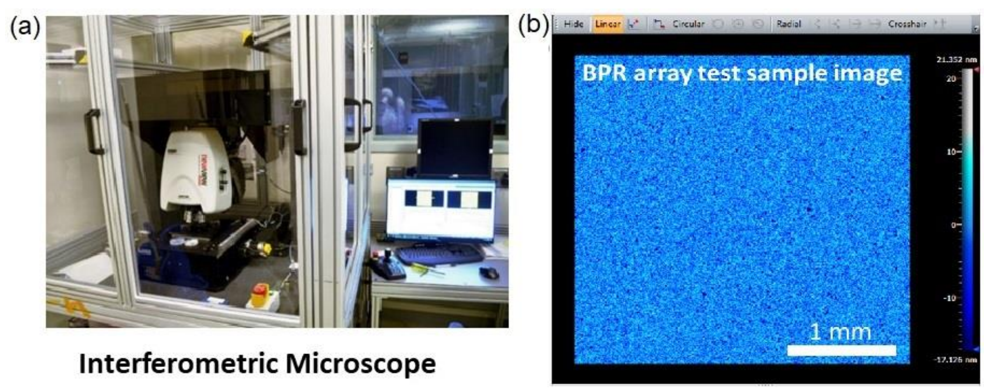

Figure 4. (a) Experimental arrangement of the interferometric microscope located in the cleanroom of the Advanced Light Source X-Ray Optics Laboratory [16,17]. The microscope is placed on a floating granite table surrounded with a plastic hutch. This arrangement ensures low sensitivity of the setup to floor vibration and residual variation of the room temperature on the level of ± 30 mK. (b) An image of the surface height topography measured with the BPRA test sample with the fundamental size of 2.5 µm.

The one-dimensional (1D) PSD distributions corresponding to the measured BPRA pattern (Fig. 4b) are presented in Fig. 5 in log/log scale (Fig. 5a), and in linear scale (Fig. 5b). The comparison between the measured PSDs (the green and purple lines with the roll-offs) and the ideal PSD inherent to the test pattern (the red-dotted- straight lines, added as a guide) allows extraction of the ITF of the microscope for this particular objective/zoom arrangement.

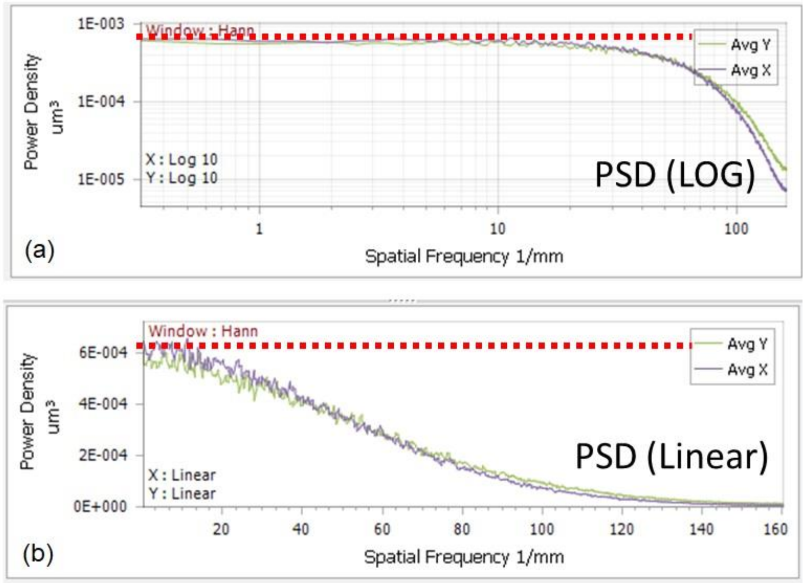

Figure 5. One-dimensional power spectral densities corresponding to the height distribution in Fig. 4b measured with the 2.5-µm BPR array pattern using the interferometric microscope available at the ALS XROL equipped with 2.75× objective and ×1.0 zoom lens. The effective pixel size of the microscope's CCD detector is 3.115 µm. The same PSD data is shown in (a) logarithmic scale, and (b) linear scale. The logarithmic scale deemphasizes the rapid decrease at mid-frequencies. Only at the lowest spatial frequencies of less than ~ 20 mm^{-1}, the ITF of the microscope is close to 1, whereas for most of the spatial frequency range available with the tool the ITF is significantly smaller.

The 1D PSD spectra shown in log scale (Fig 5a), as it is commonly presented, seems to indicate a nearly flat PSD over "most" of the operational frequency range, with an observable roll-off beginning at about 30 mm^{-1}. Looking at the same data in linear scale (Fig. 5b) gives a clearer picture: in fact, nearly the entire spatial frequency range is perturbed, with a roll-off beginning below 20 mm^{-1}, meaning that the amplitudes of surface variations with spatial frequencies from there up to the maximum spatial frequency available with the tool are not correctly reproduced. However, now that a precise measurement has been made of this problem, it can be partially mitigated by data deconvolution, as discussed in the next section.

4. DATA DECONVOLUTION USING THE MEASURED ITF

Since the BPRA-based technology allows precise numerical characterization of the ITF, data deconvolution (reconstruction) using the measured ITF becomes possible. For this purpose, we have developed the deconvolution software prototype, "SlopeReconstruction2D." This is the two-dimensional version of the 1D software used for deconvolution of surface slope data available with slope profilometers [11,12]. The new software prototype is capable for processing 2D image data, for example, recorded with Fizeau interferometers and interferometric microscopes. Like the 1D version [11,12], there are two major functionalities. First, for a precise parametrization of the analytical ITF model, convolution is applied to the inherent HR BPRA image of the sample to match the 2D PSD distribution resulting from the actual measurement of the sample. Among the built-in ITF options are the Gaussian, Sync (Box), and Circular Aperture (Airy) functions. Second, the parametrized analytical model of the ITF obtained from the first calibration step is used to deconvolve the instrument response from measured data to reconstruct the true surface topography of a surface under test.

In our previous work [11,12] on ITF calibration of 1D surface slope profilers and reconstruction of the 1D surface slope data recorded with 1D slope profilers, we have shown that application of the deconvolution technique based on high-accuracy measurement and modeling of the tool's ITF allows us to effectively recover a significant part of the higher spatial frequency information about the surface topography that is nominally lost due to the limited resolution of the slope profiler.

Similarly, the 2D deconvolution allows for a partial mitigation of the problem low fidelity in the measurements of 2D topography at higher spatial frequencies. Compared with the raw measured data, the reconstructed data can be thought of as that measured with a tool with a significantly improved ITF.

Note that improvement of the tool itself, e.g., by substituting UV light for visible light, still leaves room for the deconvolution technique to be applied to further improve data from the upgraded tool; all that is required is a new measurement of the tool's ITF.

In order to illustrate the reconstruction capabilities of the 2D software prototype, we have applied the newly developed deconvolution procedure to the data obtained in measurements with the “Beameter” test pattern available from aBeam Technologies, Inc. [18]. The “Beameter” test pattern, developed for resolution tests with scanning electron microscopes (SEMs), is a chirped height pattern with a constant amplitude (Fig. 6a). The area of the pattern measured with the ALS XROL interferometric microscope equipped with the 50× objective and ×2.0 zoom lens (Fig. 6b) is indicated in Fig. 6a with a red rectangle. The area treated with the reconstruction procedure is indicated in Fig. 6b with the white rectangle.

In this measurement configuration, the microscope has the highest possible (diffraction-limited) resolution. Though the effective pixel size of the recorded data is 87.6 nm × 87.6 nm, this is much smaller than the diffraction limit of the visible white-light tool. The effect of the limited resolution of the microscope is clearly seen in the surface height variation in the central section of the 2D height topography as a steady decrease of the amplitude of the height variation, such that the variation has nearly vanished at the end of the trace in Fig. 6c.

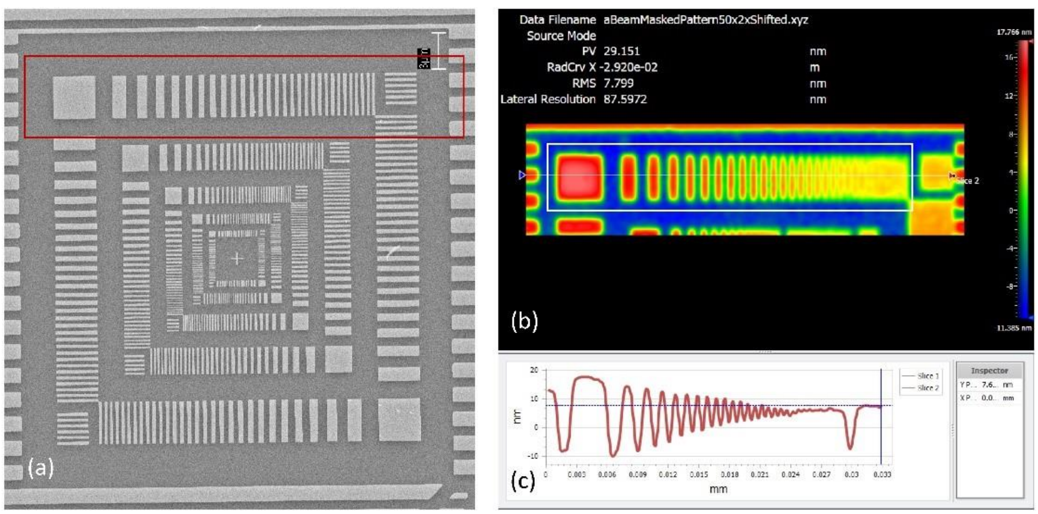

Figure 6. (a) High resolution image of the “Beameter” test pattern [18]; (b) the height distribution measured with the interferometric microscope available at the ALS XROL (equipped with the 50× objective and ×2.0 zoom lens) over the pattern area indicated in plot (a) with the red rectangle; (c) the surface height variation in the central section of the 2D height topography in plot (b).

Despite the clear indication of the resolution limit of the microscope measurements, the “Beameter” test pattern does not give sufficient information to allow calibration of surface profilometers. Like many other test samples, this test pattern is inherently one dimensional and local. Such patterns are more useful for the scanning type of data acquisition realized, for example, in SEMs. Unlike the other test samples, the HR BPRA test patterns discussed in this paper are optimal for calibration of 2D imaging (rather than scanning) surface metrology tools, such as Fizeau interferometers and interferometric microscopes.

To deconvolve the data in Fig. 6, we need to perform calibration of the microscope ITF in the same measurement arrangement. For this purpose, a BPRA test pattern with elementary size of 400 nm was used. Note that the fundamental size of the HR BPRA pattern is significantly larger than the effective pixel size of the microscope in the used arrangement. However, the sample appears to be still good for the ITF calibration of the tool with the resolution limited by diffraction of the light with the wavelength of about 550 nm.

Once the ITF function is parametrized based on the measurement with the BPRA sample (Fig. 7), using the "SlopeReconstruction2D" software, the deconvolution procedure is applied to the measured height distribution with the Gaussian-like instrument point-spread function.

Figure 7 shows the "SlopeReconstruction2D" software interface when processing the microscope ITF calibration measurements. The measured topography is shown as recorded with the ALS XROL interferometric microscope with the 50× objective and ×2.0 zoom lens. In this case, we approximate the ITF with a simple analytical model corresponding to a Gaussian-like point spread function (PSF). Incorporation into the software a more realistic ITF model based on a sophisticated theoretical model of an interference microscopes (see, for example, Ref. [19]) is work in progress.

Figure 7b shows the processed height distribution obtained by deconvolving the measured topography (Fig. 7a) using the Gaussian PSF. The parameters of the Gaussian PSF model (widths in the *X* and *Y* directions of 3 pixels and regularization parameter of 10^{-2} (for the definition, see Refs. [16,17]) were found by the best approximation of the reconstructed PSD (shown with the orange line in the plots in the right-bottom corner of the figure 7d) to a constant variation over the spatial frequency range available with the present microscope resolution (Fig. 7d). It reproduces reasonably well the resolution properties characteristic for the microscope in that configuration.

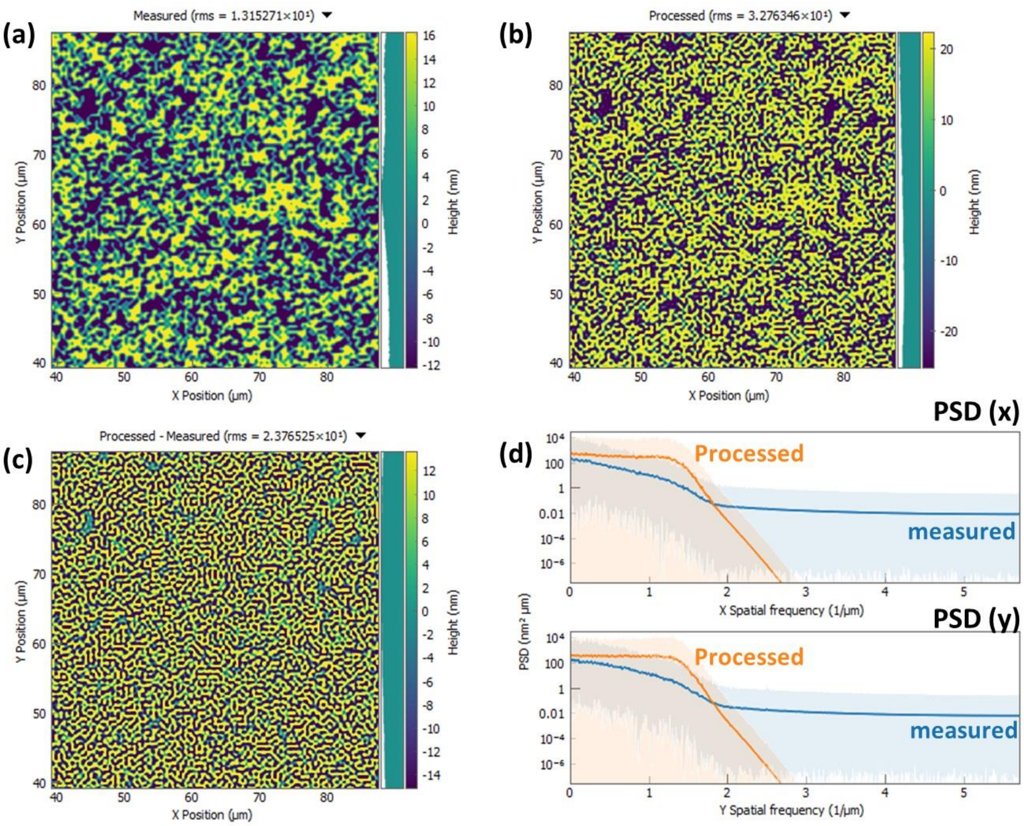

Figure 7. "SlopeReconstruction2D" software interface when processing the microscope ITF calibration measurements performed with the 2D HR BPRA test pattern with the elementary size of 401 nm and 30-nm depth. The calibration data were taken with the ALS XROL interferometric microscope with the 50× objective and ×2.0 zoom lens. The processed height distribution was obtained by deconvolving the measured topography with the Gaussian-like PSF. For proper parametrization of the Gaussian PSF, we use the HR BPRA property of independence of the inherent PSD from the spatial frequency (compared with the PSD of the reconstructed topography shown with the orange lines in the plot in the right-bottom corner of the figure).

Once the ITF is parametrized based on the measurement with the BPRA sample (Fig. 7), using the "SlopeReconstruction2D" software, the deconvolution procedure can be applied to the measured height distribution of the aBeam "Beameter" test pattern in Fig. 6.

Figure 8a reproduces the measured topography of the aBeam “Beameter” test pattern as taken with the microscope equipped with the 50× objective and ×2.0 zoom lens and cropped as indicated in Fig. 6b with the white rectangle. The processed height distribution in Fig. 8 was obtained by deconvolving the measured topography with the Gaussian-like PSF parametrized in the calibration measurements depicted in Fig. 7. The visual sharpness of the processed 2D height distribution is also significantly improved (Fig. 8b). The effect of the reconstruction is seen as a significant increase of the amplitude of the oscillation in the cross-section of the reconstructed topography. Figure 8c shows the horizontal cross section from plots (a) and (b), the reconstructed data (in orange) recovered nearly a factor of 3-4 times more in height amplitude compared to the measured data (in blue). This is the first demonstration of the efficacy of the developed HR BPRA based 2D ITF calibration and data reconstruction in application to an industrial interferometric microscope.

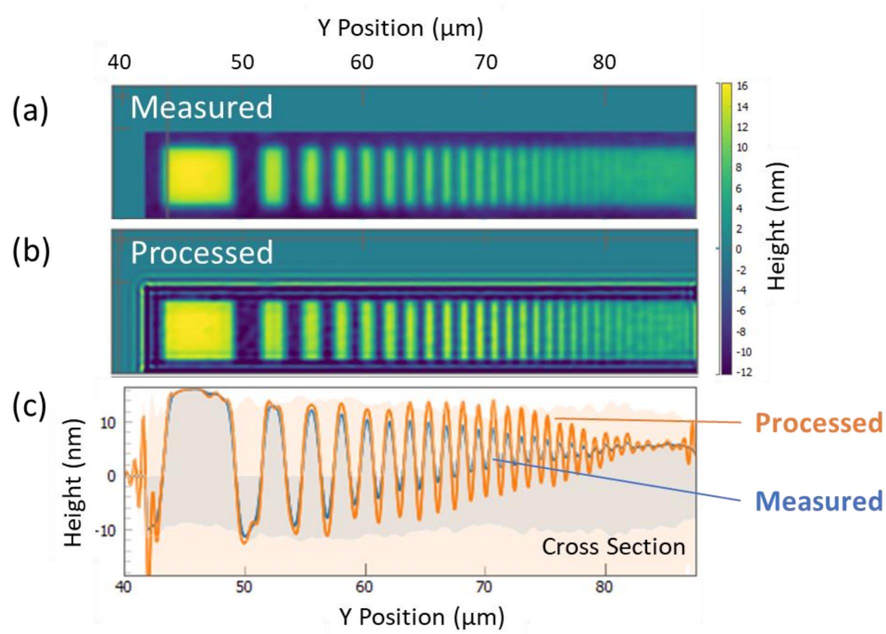

Figure 8. The measured (a) and reconstructed (b) topographies of the aBeam “Beameter” test pattern processed as discussed in the text and illustrated in Fig. 7. (c) The horizontal cross-section of the measured and reconstructed topographies to demonstrate the increase of the variation amplitude as the result of the applied deconvolution procedure.

In Fig. 8, we use the same height scale for the two distributions to make more visible the improvement of the sharpness of the processed 2D height distribution. The contour-like artifact in the processed image is due to the approximate character of the Gaussian-like PSF used for the data deconvolution.

5. CONCLUSION

We have presented and discussed the BPRA test sample-based technology that allows for comprehensive characterization of imaging tools (via ITF calibration) and subsequent data-deconvolution (reconstruction) based on the measured ITF and its precisely parametrized model.

An example of the application of the technology to calibrate an industrial interferometric microscope has shown a large attenuation of the signal over a large portion of the available spatial frequencies. Using the precisely characterized ITF, an example of data-reconstruction was shown using a commercial chirped grating test pattern. The data reconstruction has allowed us to recover a factor of 3-4 higher amplitude of the surface height variation of the sample compared with the raw data compromised by the limited spatial resolution of the microscope.

To the best of our knowledge, this is the first commercially available product for surface topography reconstruction based on ITF calibration of 2D metrology instruments used for optical surface characterization. In the future, the same techniques can be applied to a wide range of metrological systems using the same principle of BPRA test sample-based ITF characterization and data reconstruction.

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DISCLAIMER

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