

Advanced X-ray phase-contrast and dark-field imaging with the unified modulated pattern analysis (UMPA).

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In the last decades, X-ray phase-contrast (XPCI) and dark-field imaging (XDFI) methods have been extensively explored for applications in the areas of biomedical imaging, materials science, and many more. Among the various XPCI and XDFI techniques, X-ray near-field speckle-based imaging (SBI) [1-3], only recently developed, has shown tremendous potential for multi-contrast imaging applications, as well as metrology and wavefront sensing. The method is based on analyzing the sample-induced modulations of a near-field speckle interference pattern created by a phase modulator, to retrieve the absorption, refraction and small-angle scattering information of the specimen. The simple setup and moderate coherence requirements make SBI an attractive technique for widespread implementation at synchrotron and laboratory facilities. Some limitations of the early operational modes were tackled by our recently proposed unified modulated pattern analysis (UMPA) [4], allowing flexible tuning of signal sensitivity and spatial resolution. Here, we show the applications of UMPA for multimodal imaging [4] and optics characterization [5]. We further present our most recent results on UMPA phase tomography of biomedical specimens and demonstrate the great potential and flexible character of the approach.

Measurements were conducted at beamline I13 of Diamond Light Source and ID19 of the European Synchrotron Radiation Facility with monochromatic X-rays and filtered white and pink beams from undulator sources. Sandpaper was used as a diffuser to create a speckle pattern that was recorded in the near field using a detector system consisting of a scintillation screen coupled to magnifying optics and a CCD camera. Reference and sample images were acquired without and with the object in the beam, respectively. Several diffuser positions with irregular, large spacing were used. Data analysis was performed following the UMPA formalism [4], based on a model of the sample speckle pattern that considers the effects of intensity reduction, displacement and loss in amplitude of the reference pattern due to the presence of the sample. A windowed least-squares minimization between modeled and measured sample pattern, summed over all diffuser positions, delivers the multimodal signals for each pixel. Data was acquired in projection and tomography mode. For the latter, the multimodal signals were reconstructed for each projection, followed by a filtered back-projection step to obtain the tomograms.

Figure 1 shows the first results of UMPA for multimodal imaging on a small flower bud reconstructed from a scan with $N = 24$ diffuser positions and an analysis window w of 5×5 pixels [4]. The information from the high-contrast differential phase signals in (a) and (b) is complemented by the transmission (d) and dark-field (e) images. The absolute phase shift in (c) is obtained from (a) and (b) via 2D integration. The sensitivity σ and spatial resolution of the results can be tuned by the choice of N and w . Sensitivities of $\sigma_x = 79$ nrad and $\sigma_y = 66$ nrad were achieved for the results in Fig. 1. The resolution limit of UMPA is

given by twice the full width at half maximum of the window, here 4 pixels $\approx 1.6 \mu\text{m}$. It was also demonstrated that UMPA can be employed for accurate and precise optics characterization [5]. Different kinds of polymer X-ray refractive lenses were examined and slope errors caused by shape deviations and beam damage were identified and quantified, see Fig. 2. UMPA was recently extended from 2D projection imaging to 3D tomography and applied to the investigation of biomedical soft tissues. The differential phase signals in x and y of one of the tomography projections of a mouse testicle (in a plastic tube) can be seen in Fig. 3. Already in the projections the fine structures inside the testicle are outlined. The phase volume, obtained via filtered back-projection, quantitatively reveals the detailed inner density distribution and allows visualizing the seminiferous tubules with high contrast. Images were acquired with $N=20$ and $w=5\times 5$ pixels for Fig. 3. To minimize scan time and dose, but keep a comparable signal sensitivity, this could be reduced down to $N=5$ by increasing w , at the cost of a lower spatial resolution.

We have demonstrated the potential of UMPA for imaging and metrology applications in projection and tomographic implementation. The flexible and tunable nature of UMPA allows one to tailor the scan and reconstruction parameters to the desired spatial resolution and signal sensitivity. Combined with the ease of setup and the applicability to different kinds of reference patterns, UMPA is expected to be widely implemented for a large number of applications, in particular for biomedicine and materials science [6].

References:

- [1] S Berujon *et al*, Phys. Rev. Lett. **108** (2012) 158102.
- [2] KS Morgan, DM Paganin and KKW Siu, Appl. Phys. Lett. **100** (2012) 124102.
- [3] S Berujon, H Wang and K Sawhney, Phys. Rev. A **86** (2012) 063813.
- [4] M-C Zdora *et al*, Phys. Rev. Lett. **118** (2017) 203903.
- [5] M-C Zdora *et al*, Opt. Express **26** (2018), p. 4989-5004.
- [6] The authors acknowledge T. Zhou (Diamond), F. Koch (LMN/PSI), J. Romell (KTH), S. Sala (UCL, Diamond), A. Last (IMT/KIT), Y. Ohishi (JASRI), and N. Hirao (JASRI) for their contributions.



Figure 1. Multimodal signals of a flower bud obtained with UMPA: (a) Refraction angle in x , and (b) in y , (c) integrated phase, (d) transmission, (e) dark-field. Reprinted from [4], licensed under CC BY 4.0.

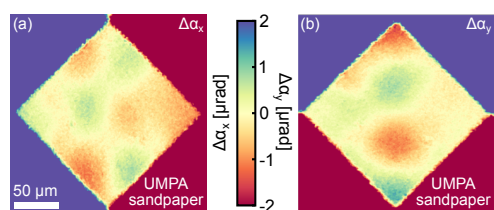


Figure 2. Refraction errors of a point-focusing polymer X-ray refractive lens in the (a) horizontal, (b) vertical direction obtained with UMPA analysis. Reprinted from [5], licensed under CC BY 4.0.

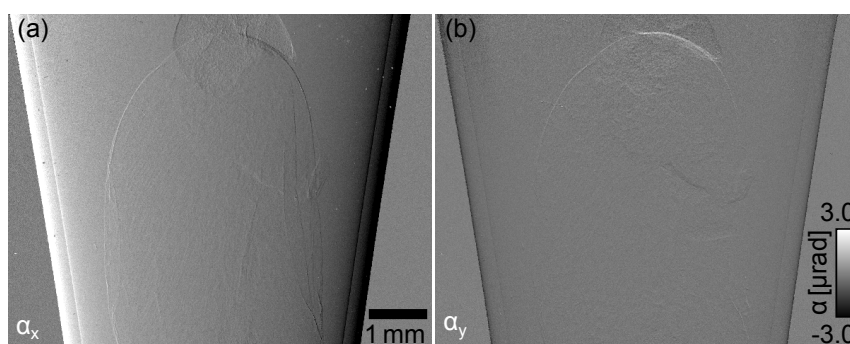


Figure 3. First projection of the tomogram of a mouse testicle. Refraction angle signal in (a) horizontal and (b) vertical direction.