Investigation of Split-And-Delay Unit flatness using White Light Interferometry

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Abstract.

The goal of this project is to investigate split-and-delay unit surface using white light interferometry. The SDU allows to get interferometric pump–probe experiments with short XUV laser pulses and X-ray beams provided. In this work LabVIEW program is used for doing measurements.

Contents

1. Introduction

Flatness is important property for functional surfaces, for example in optics. In this work flatness of a split-and-delay unit (SDU) was studied using white light interferometry. The SDU allows to split the X-ray beam into two beams with a delay of several femtoseconds, which allows to study molecules and chemical reactions.

Why the SDU is needed for X-ray experiments instead normal (glass) beam splitter?

X-ray radiation is electromagnetic radiation with wavelengths in the range of about 0.01 to 150 nm. The interaction of X-rays with the electrons of an atom in a substance is described by the complex dielectric constant ε, which gives a complex refractive index n:

$$\bar{n} = \sqrt{\bar{\varepsilon}} = 1 - \delta - i\beta \qquad (1)$$

where:

δ – refractive index decrement;

β – absorption coefficient.

Since the refractive index of less than 1, the X-ray radiation incident on the substance is totally reflected if the grazing angle θ is smaller than the critical angle θ_c:

$$\theta_c = \sqrt{2\delta} \qquad (2)$$

Conventional mirrors are not very applicable to X-ray radiation, because in the beam incidence (close to normal), the ratio of the intensities will be reflected radiation I to the incident I_0:

$$\frac{I}{I_0} = \frac{(\delta^2 + \beta^2)}{4} \qquad (3)$$

Due to the smallness of δ and β, the reflection is extremely insignificant. The situation changes at angles of incidence close to 90 ° (the case of grazing incidence). Since X-rays fall from a substance with a higher refractive index (vacuum) onto a substance with a lower refractive index (for X-rays any substance has n<1), the wave cannot penetrate into the substance, and the incident radiation will be reflected back into the first substance like to the total internal reflection for visible light [1].

White light interferometry (WLI) was chosen for this task. WLI is widely used for profile characterization of both dynamics and static surfaces with sub-nanometer precision. As any interferometry technique, WLI utilizes the superposition property of electromagnetic waves, i.e. their ability to interfere when superimposed.

2. Theory

2.1. Autocorrelation

Autocorrelation is the relationship between a signal and delayed copy of itself as a function of delay. In other words, this is a mathematical representation of how similar a given time series and its lagging version are [2]. It is the same as calculating the correlation between two different time series, except autocorrelation uses the same time series twice: once in its original form and once lagged one or more time periods.

Autocorrelation measures linear relationships; even if the autocorrelation is small, there may still be a nonlinear relationship between a time series and a lagged version of itself.

The intensity of autocorrelation $A^{(2)}(\tau)$:

$$A^2(\tau) = \int_{-\infty}^{\infty} I(t)I(t-\tau)\mathrm{d}t \qquad (4)$$

where:

τ – shift in time;

t – time;

I – signal intensity.

Correlation can be nonlinear if the coefficient of change is not constant. In other words, when all the points on the scatter diagram tend to lie near a smooth curve (not straight line), the correlation is said to be nonlinear (curvilinear) [3].

2.2. White Light Interferometry

Interference is a phenomenon in which two waves overlap to form a resultant wave of greater, lower, or the same amplitude. Interference is the result from the interaction of waves that are correlated or coherent with each other (because they come from the same source or because they have the same or nearly the same frequency) [4].

White light interferometry is a non-contact optical method for surface height measurement on 3D structures with surface profiles.

White light interferometers use the interference effects that occur when the light reflected from the sample is delayed on with the light reflected by a high-precision reference mirror [5].

The measurement method is based on the principle of Michelson interferometry, where the optical configuration (Fig. 1) contains a light source with a coherence length in the μm range. The collimated light beam is split into a measurement beam and a reference beam at a beam splitter. The measurement beam hits the mirror M2, the reference beam gets into a mirror M1. Light reflected from the mirrors is recombined at the beam splitter (cube) and focused onto a camera.

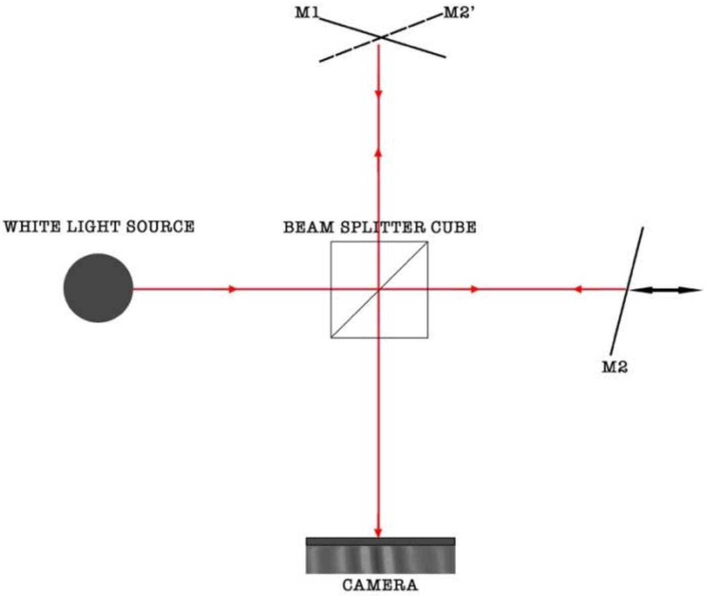


Fig. 1. White light interferometer. M1 – reference mirror, M2 – surface profile (mirror), M2' - reflected image of mirror M2. M2' image obtained by reflection from a dielectric coating in a beam splitter cube.

When two beams intersect at an angle θ, they form an interference pattern in the intersection area. The grating is characterized by the grating vector $\mathbf{k_g} = \mathbf{k_1} - \mathbf{k_2}$, where $\mathbf{k_1}$ and $\mathbf{k_2}$ are the wavevectors of the intersecting beams [6].

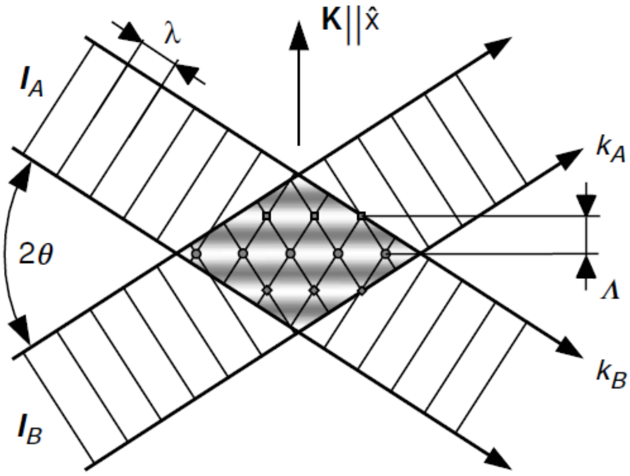


Fig. 2. Interference pattern grating formed by two beams linearly-polarized perpendicular to the image plane.

If $|\mathbf{k_1}| = |\mathbf{k_2}|$ the grating period Δ along $\mathbf{k_g}$ depends on the wavelength and the intersection angle as:

$$\Delta = \frac{\lambda}{\sin(\theta)} \qquad (5)$$

The grating has a fixed period, but positions of minima and maxima "scroll" inside the beam intensity envelope depending on the temporal phase difference between the two beams.

3. Experiment and results

3.1. Experimental setup

In this experiment was investigated split-and-delay unit (SDU). This device is used to produce a double pulse sequence by splitting a given initial pulse in two replicas, delay one of them in time, and then overlap both in space [6]. The construction consists of two comb mirrors inserted into each other. The grid of first mirror has a period of 250 µm, with 150 µm wide, 10 mm long slits and 100 µm wide stripes of material between them. When interposed the two mirrors form a sequence of 100 µm wide and 25 µm spaced stripes between them (Fig. 3). Delay is generated by displacing one of the mirrors along the surface normal.

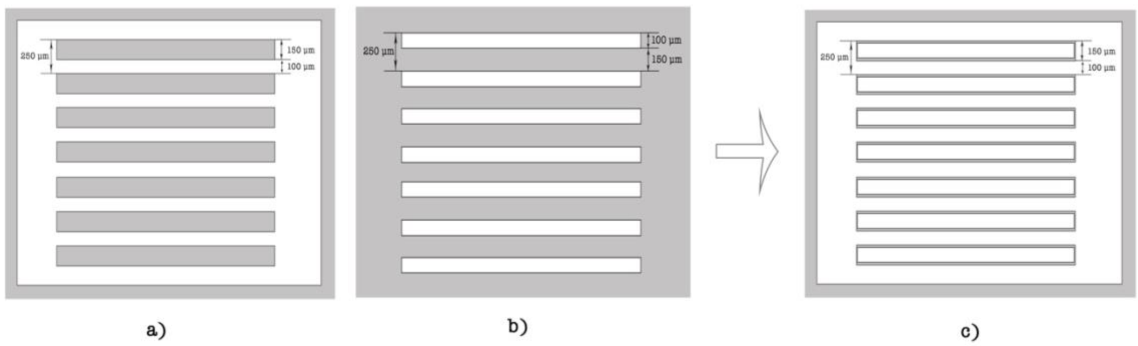


Fig. 3. Two components of the SDU: a) and b) are the two comb mirrors and c) shows their arrangement when interposed.

3.2. Measurements

The surface quality and flatness of the two mirrors was tested with a white light interferometer. During summer program there were three main experiments.

1) For a first experiment small regions were measured with different conditions: for a first measurement experimental stage was on solid feet and for second one on vibration dampening feet. Setup design consists of three feet and an experimental stage on top. VIB100 Vibration Isolators were used for this experiment. After, these two results were compared to each other to determine the best one.

2) For a second experiment were measured two different regions at the same time: one at the top and one at the bottom (Fig. 4). It shows the difference in surface flatness at the upper and lower parts of the mirror.

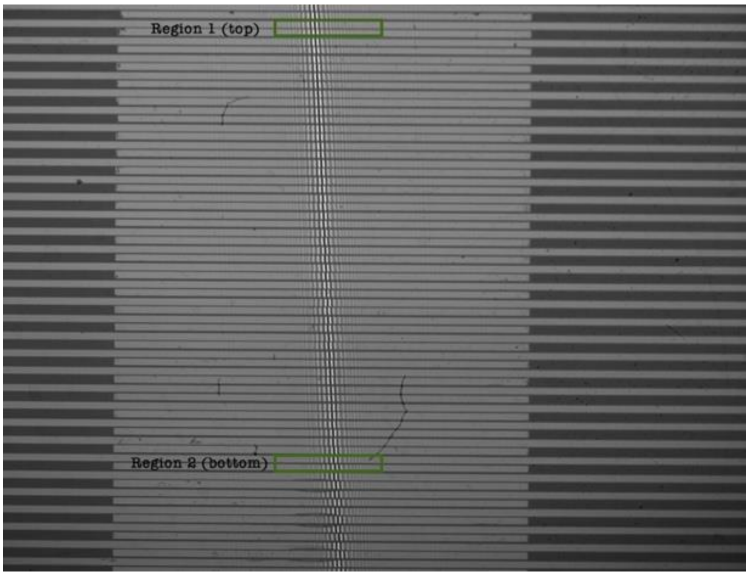


Fig. 4. Two selected regions at comb mirrors for measuring.

3) For a third one some areas 3,5 mm x 1,5 mm at the SDU surface were chosen for studying the surface flatness (Fig. 5).

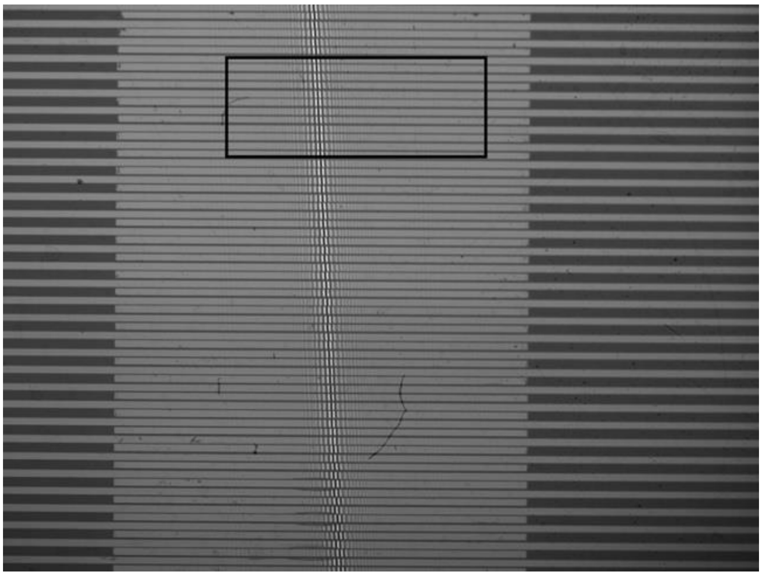


Fig. 5. Selected region for measurement 1,5x3,5 mm size.

Black stripes and dots at the mirror surface probably dust or scratches. For measuring we selected areas without damage.

A white light diode with a mean wavelength λ = 593 nm as the illumination source is used in the interferometer. The diode is mounted on top of the vacuum chamber and illuminates the interferometer through a viewport. The beam from the diode is split equally into two beams by beam splitting cube [6].

All measurements were done via LabVIEW program. The LabVIEW program is intended to optimize and automize the measurements. It allows to move the delay stage, change the position of mirrors and the angle between them. Via LabVIEW is possible to select the regions of interest, set number of steps, and so on. In this program the file format can be specified for output data files.

3.3. Results

During this summer program some Python and Matlab codes were written. Processing of first and second experiment measurements were done via Python 3.6 (Spyder). For heightmaps experiment (Fig.4) data processing was done via Matlab.

1. <u>First experiment</u>: comparison of measurement results with solid feet and vibration dampening feet. So, we can determine which feet for a stage are better suited for experiments.

   Also, the same regions were measured without white light – this is just background.

Steps:

1) Firstly, to obtain clean results the background substrate is needed.

- load the background;
- load the data and set parameters;
- substrate the background;

2) Select regions of interest (by red and blue dotted lines). For this we specified a1, a2, b1, b2 variables in pixels at Y axis

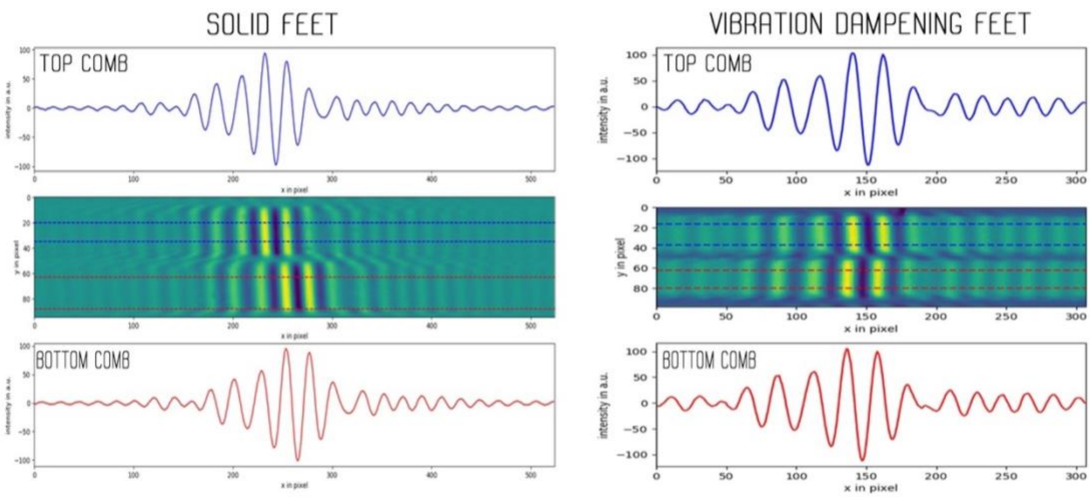


Fig. 6. Comparison of two different measurements. Blue and red graphs show an intensity of stripes at pictures.

3) Next main step – a cross-correlation of two signals from two different regions. Cross-correlation is a measure of similarity of two series as a function of the displacement of one relative to the other.

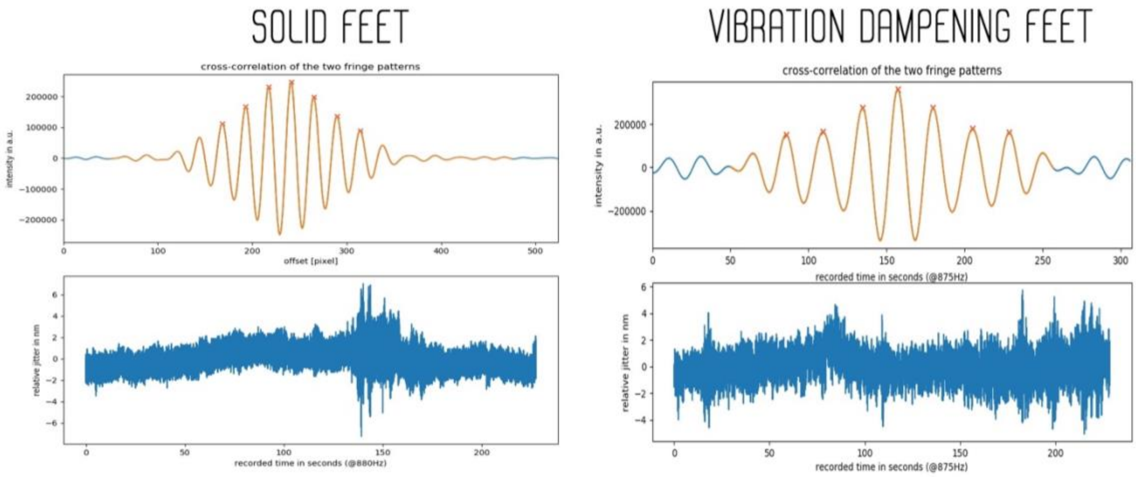


Fig. 7. Result of a cross-correlation for tops and for bottoms combs and relative jitter of cross-correlation.

For graphs in the first line: the blue line is a cross-correlation, the orange one – the result of interpolation with 100 steps in between each datapoint of this line. Also, several main peaks are marked by red crosses.

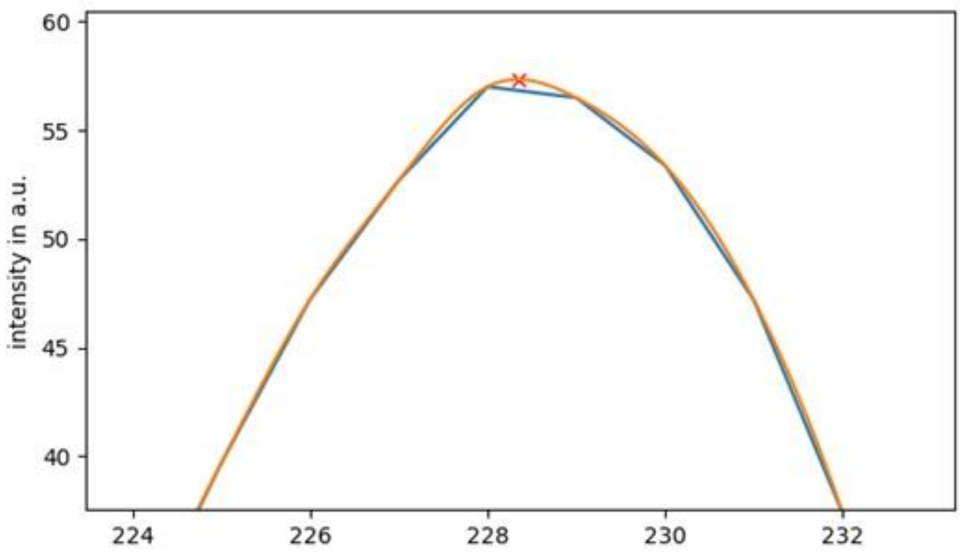


Fig. 8. Difference between cross-correlated line (blue) and their interpolated version (orange). The red cross is a peak position.

4) And the last step is Fast Fourier Transform (FFT) for relative jitter. It was made with numpy.fft.fft() function.

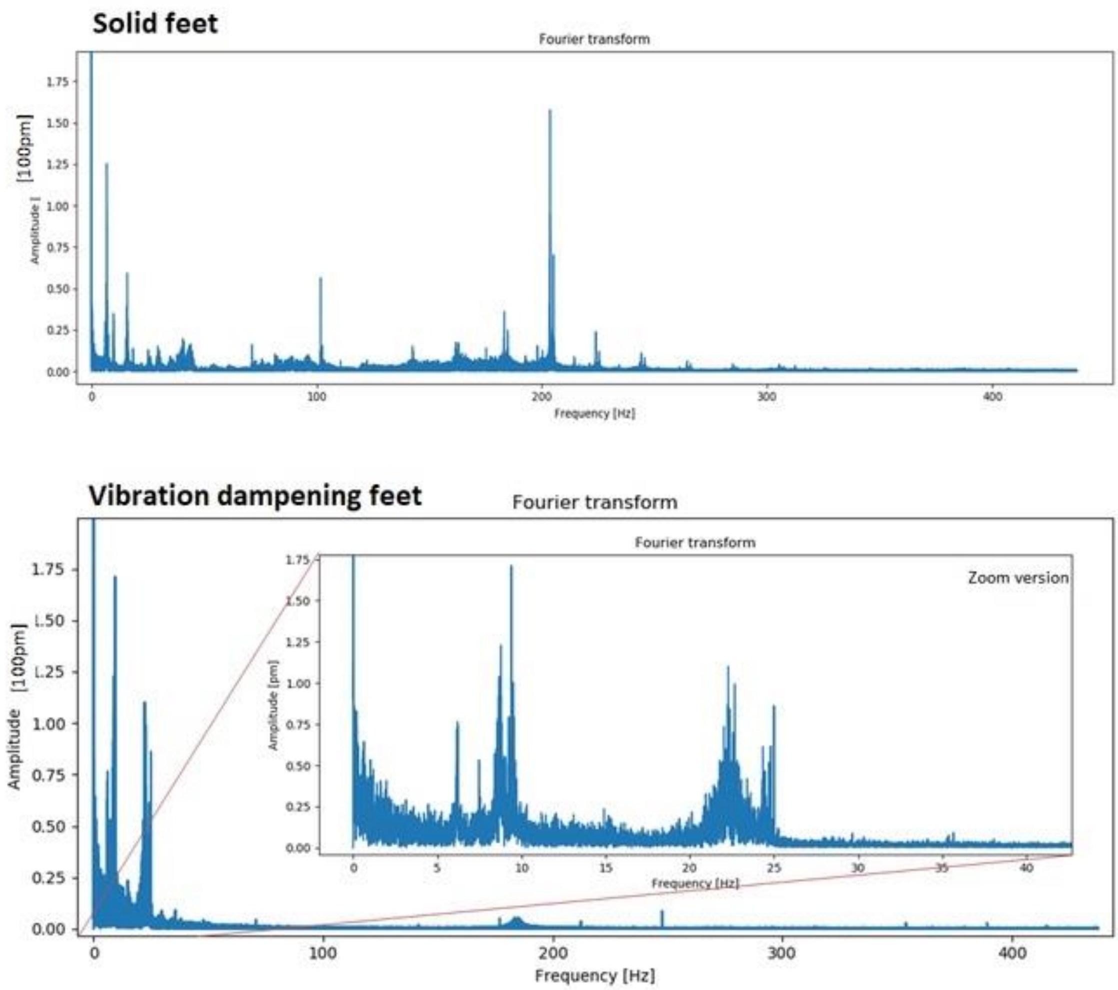


Fig. 9. Results of FFT for solid feet and vibration dampening feet.

Comparing these two results, we can see peaks with same frequencies but with different amplitude. The Fourier transformations (Fig. 9) show that the stage with the vibration dampening feet absorbs vibrations at frequencies greater than ~25-30 Hz. It means that the vibration dampening feet filter out a broad band of input vibration frequencies and insure a constant level of vibration transmission reduction. The lower frequencies are then much slower the camera frame rate of 60 to 800 fps and illumination times below 1 μs.

2. <u>Second experiment (pitch angle measurement):</u> the measurement of two different regions at the same time (one at the top and one at the bottom). So, we want to compare the top and the bottom regions (Fig. 3). In this experiment a background was also measured.

Steps are almost the same as at for the first data processing:

1) Background subtracting
2) Set parameters
3) Select regions of interest (by red and blue dotted lines)

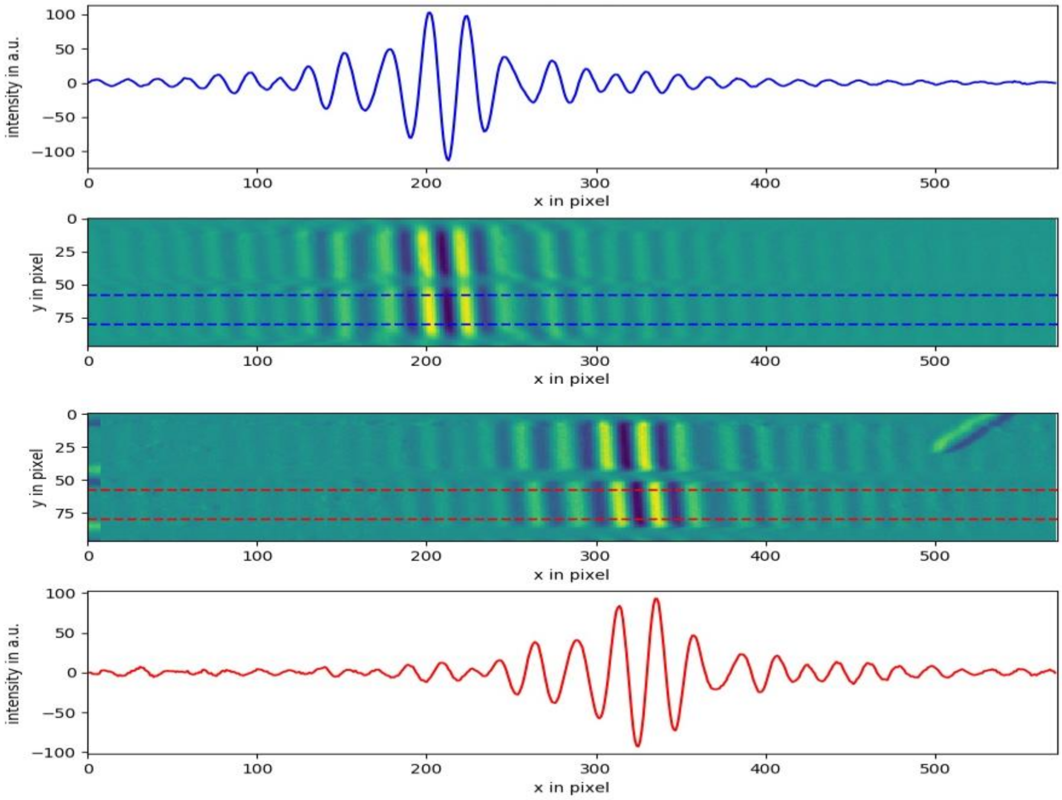


Fig. 10. Comparison of the movement two regions of the bottom comb.

4) A cross-correlation of two signals from two different regions. In this case we did cross-correlation not for top and bottom comb, but for two top/two bottom combs from different regions.

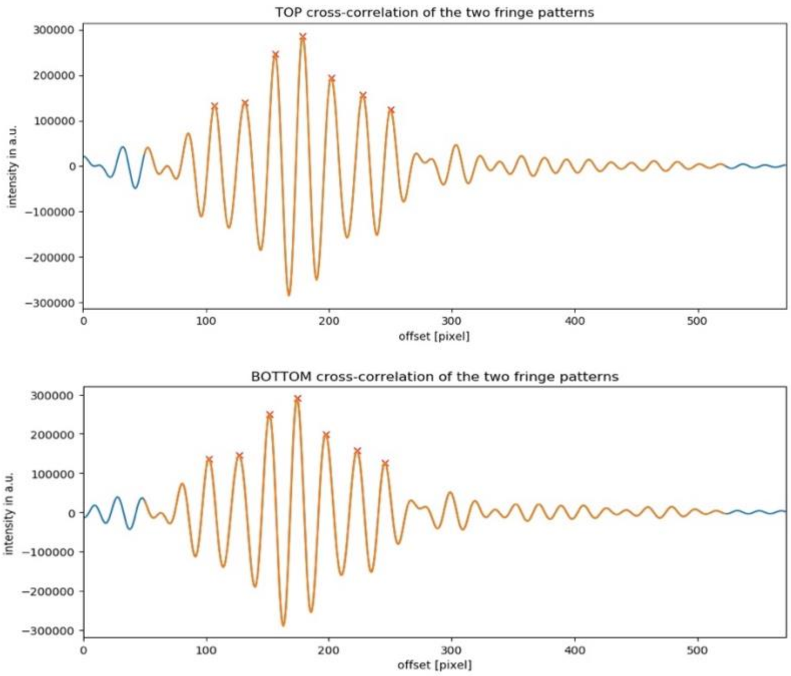


Fig. 11. Result of a cross-correlation for tops and for bottoms combs.

5) And the last step for changing of the angle.

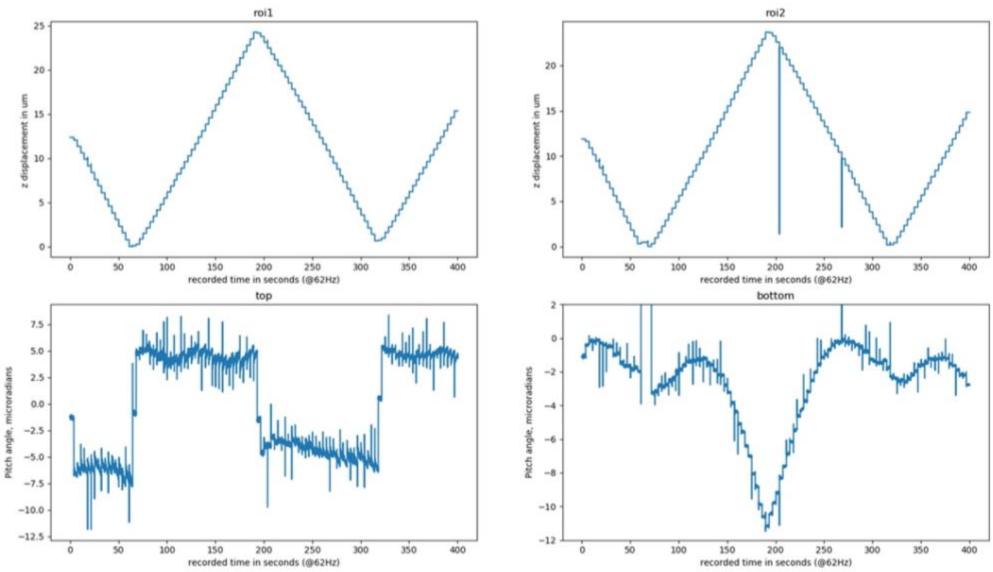


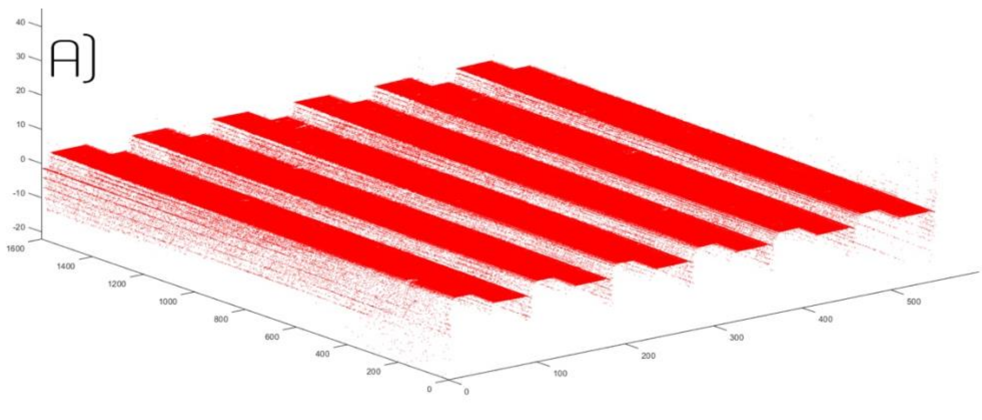
Fig. 12. Time-dependence of a pitch angle. For this calculation 20000 frames were used.

The first row at fig. 12 shows the movement of the bottom comb at each ROI. The measurement was done in 1V steps equaling around 0.7µm every 5 seconds. The peaks mean changing the direction of movement (forward-backward-forward). Changing the position of the combs was done by hands, not automatically. This may be the reason of different step length over time.

At the second row we can see that a pitch angle of the top comb stays almost constant when movement goes in one direction. When the direction of movement changes, the angle also changes a lot. The pitch angle of the bottom comb changes with the comb moving.

During the scan the pitch angle of the top comb only changes by about 2-3µrad, while the bottom comb moves repeatably between 0 and -11.5µrad. Because the combs in this setup are slightly in contact, whenever the direction of the movement of the bottom comb changes it pushes or pulls on the top comb and the pitch angle changes.

3. Third experiment (heightmaps experiment): investigation of area 1,5x3,5mm2. During this experiment the same area was measured several times (it took 3-4 days). The heights of the individual pixels were fitted in LabView and additional data processing shown below was done in Matlab.



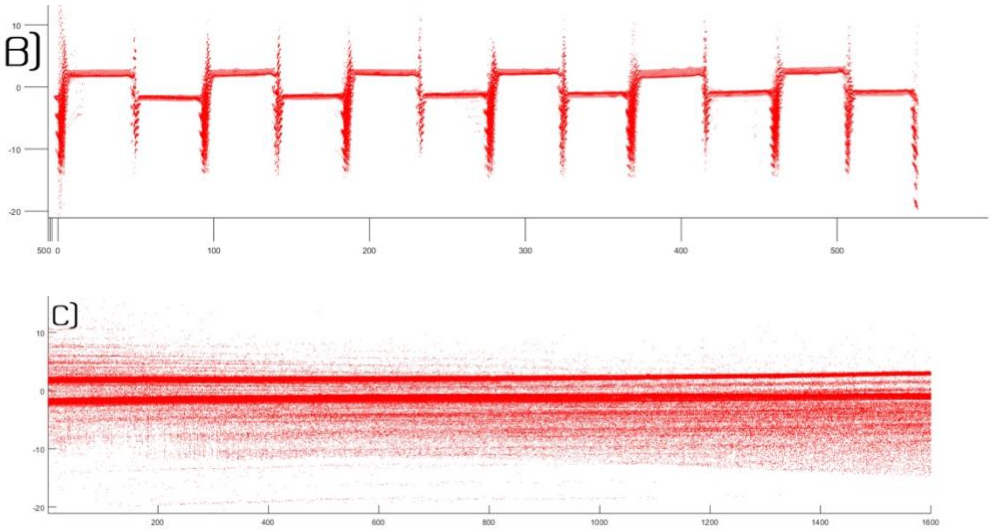


Fig. 13. Surface of the SDU region (a), its XZ view (b) and YZ view (c). X and Y in pixel, z in a. u. Averaged over 5 measurements.

In Fig. 13 the two single combs are visibly displaced. In the next step, the datapoints of each comb were separated and the individual slopes subtracted (In the following, the top comb will be shown in red and the bottom combs in blue).

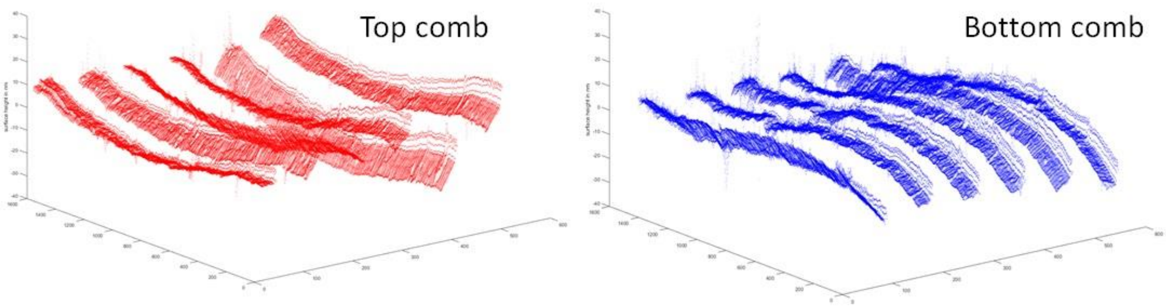


Fig. 14. The surfaces of top and bottom combs. This image is the average result of 5 measurements.

After splitting, this is possible to build heightmaps for both combs separately.

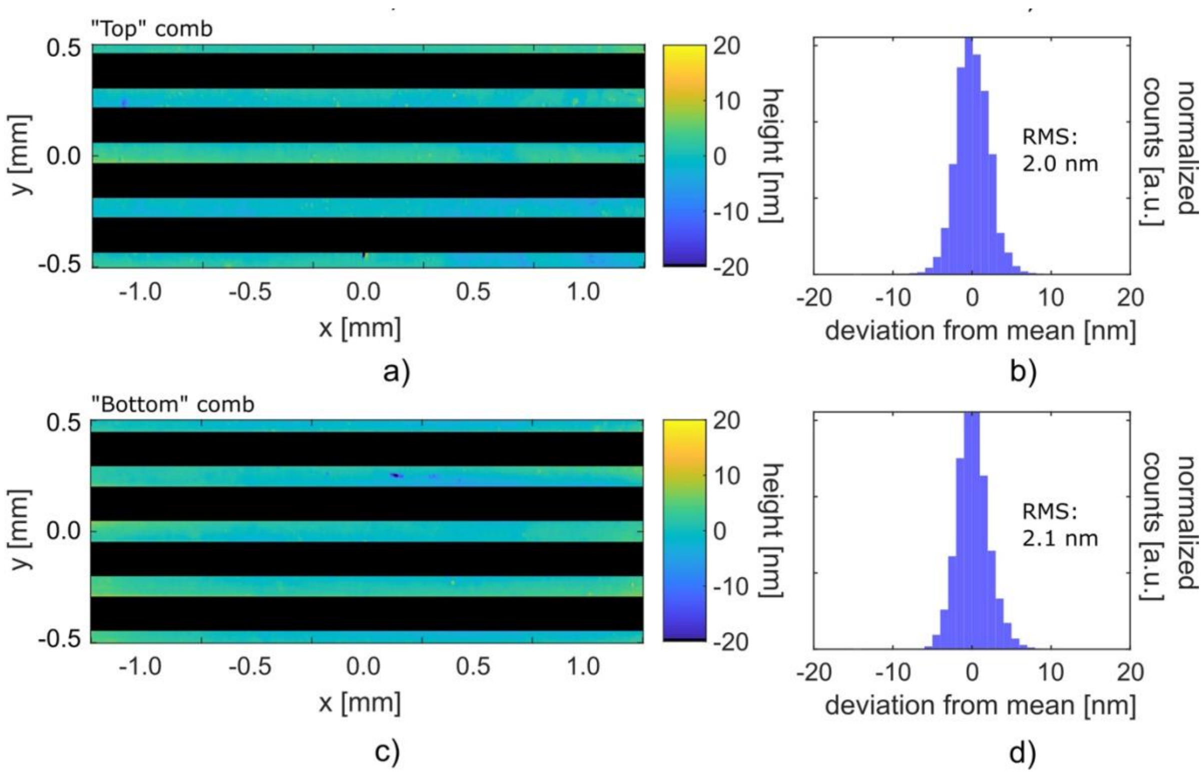


Fig. 15. Heightmaps of the top and the bottom combs (a, c) and their height distribution (b, d).

Fig. 15 presents the height distribution of the combs. Root mean square (RMS) of both distributions has a small value (2.0 nm and 2.1 nm). This means that that the SDU has a high degree of flatness and can be a good device for X-ray experiments.

4. Conclusion

During the first part of the experiment we tested the damping properties of the mechanical vibration isolators VIB100-0205 from Newport in our interferometric setup. They proved to filter out a broad band of input vibration frequencies and insures a constant level of vibration transmission reduction.

The second experiment shows how the top and the bottom combs of the SDU interact and affect each other. Because the combs in this setup are slightly in contact, whenever the direction of the movement of the bottom comb changes it pushes or pulls on the top comb and the pitch angle changes.

During the third experiments we investigated the split-and-delay unit surface using white light interferometry. Results show that the SDU has a high degree of flatness and can be a good device for interferometric pump–probe experiments with short XUV laser pulses and X-ray beams provided.

5. Acknowledgments

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6. References

[1] В. Е. Сторижко, “Способы фокусировки рентгеновского излучения”, Успехи физ. мет. / Usp. Fiz. Met., т. 11, сс. 1—17, 2010

[2] https://www.investopedia.com/terms/a/autocorrelation.asp

[3] https://www.emathzone.com/tutorials/basic-statistics/linear-and-non-linear-correlation.html

[4] Wymke Ockenga, “Phase Contrast”, 2011

[5] Prof. Dr. Albert Weckenmann, "Optical surface metrology complements tactile measurement techniques", Interview, Polytec InFocus, 2016

[6] Sergey Usenko, “Interferometry on small quantum systems at short wavelength”, doctoral thesis, 2016