Opinion on

Dissertation for the degree of Doctor of Philosophy by

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„Laboratory Soft X-Ray Microscope based on
Incoherent Capillary Discharge Source”

PhD dissertation of Mister Muhammad Fahad Nawaz discusses the design and development issues of the first soft X-ray microscope based on an incoherent capillary discharge source. The imaging with Soft X-ray radiation is often considered due to the present absorption for biological materials allowing for both phase and amplitude imaging. I believe that the thesis topic is interesting, scientifically valid and solves important technical problems, and its realization can bring new scientific and technical developments.

The dissertation consists of 95 pages and collects the number of 69 bibliographic entries that allow to get acquainted with the state of research on the issues under consideration. The work consists of four parts: the initial (chapter 1), state of the art (chapters 2 and 3), design, development and evaluation (chapters 4 and 5) and a summary (chapter 6). These parts were included in six chapters and a list of references, including the publications of the author.

In the first chapter, a doctoral student outlines the area of the subject, the structure of the work, and formulates the purpose of this PhD thesis. I believe that the aims of the work are up to date, and its implementation could bring important new scientific and technical developments.

The second chapter presents important practical fundamentals of the soft X-ray imaging. It summarizes important elements of the soft X-ray microscopic imaging in the water-window spectral region including the fundamentals of soft X-ray physics, available sources, optics and detectors. From the Thesis perspective the most important are the review of X-ray sources and available optical elements. Presented material is interesting, and well discussed. There are few important comments to this chapter:
- On the page fifteen author discusses effect of aberrations. Presented optical solutions in Sec. 2.4.1.1 do not go beyond aberration free imaging of axial point. In such a case only spherical aberration is present and eliminated. Author could be more specific if off axis aberrations are important or if the source in the design is small. If one can assume the case of axial imaging condition the geometry of the selected elliptical condenser is well chosen.
Discussing the design issues of the diffractive lens in Section 2.4.2 author applies conjugation simplification. In the design of diffractive lens the concept of Fresnel zone plate is applied that is valid for infinite object conjugation. It is also possible to design diffractive lenses that works for finite conjugations. Please consult the work by Hazra et al. [1]. How different would be a diffractive lens if this more accurate conjugation condition is applied? Probably the difference would be very small since the imaging diffractive lens works approximately at conjugation of infinite image.

- There is another remark to the design of diffractive lens objective. It is designed using concept of thin element approximation. The designed diffractive lens is deep; its depth in relation to the wavelength is large: 130nm/2.88nm = 45. There is a question of the accuracy of this approximation. Maybe using a more accurate extended scalar diffraction theory [2] would be beneficial. If not, it should provide more accurate measure of diffraction efficiency. Moreover the thesis solely discusses diffraction efficiencies of the gratings. Extended scalar diffraction theory allow evaluating diffraction efficiencies well.

The third chapter discusses known designs of the soft X-ray microscopes. There are two geometries illustrated, one based on the Fresnel zone plate and the other on the detector scanning. The end of this chapter is devoted to the methods of phase contrast imaging. The chapter is very small, it has only five pages, while the State of the Art in PhD thesis shall have more details and have to be compared with the developed X-ray microscopes. Summarizing, there are two important comments to this chapter:

- The thesis shall contain comparison of the build X-ray microscope with the other known X-ray imaging techniques presented in the State of the Art. The comparison could have the form of the table, which contains the most important practical parameters of the microscopes.

- The last page of this chapter discusses methods of the phase contrast imaging, which is possible with the build X-ray microscope. This type of imaging is beyond the scope of this thesis and therefore discussion can be concise. However there are only qualitative phase imaging methods mentioned, like the Zernike phase contrast or the differential interference contrast. There are known also the quantitative phase imaging techniques that should be included in the State of the Art chapter. One known quantitative phase imaging technique is based on the Transport of Intensity Equation [3,4] while the other on the Contrast Transfer Function [5,6]. Especially that the above quantitative phase imaging techniques do not require direct access to Fourier plane, which is advantageous considering developed in the thesis X-ray microscope.

The chapter four discusses the design and development issues of the built full-field transmission soft X-ray microscope. The most important discussed elements are: radiation sources and its characterization, condenser system, imaging system and finally full microscope system. There are two comments to this chapter:

- On the page 54 there are results of ray tracing simulation of focusing by the ellipsoidal condenser mirror. This simulation is presented as to show theoretical limits of focusing by the ellipsoidal condenser. The simulation is presented after discussing several practical steps that were considered for the ellipsoidal condenser as reflectivity, geometry, alignment, and evaluation of experimental focus spot. The order of presentation shall be different. The design issues, including simulation shall be presented at first and after that the practical aspects.

- The chapter four discusses the issues of image formation by the designed microscope. It is assumed that the numerical aperture of the objective lens and condenser lens are equal. Thus incoherent illumination conditions can be assumed. In the microscope system condenser illuminates the object with NA excluding the center cone “doughnut like angular illumination”. Since the center angles are missing their effect shall be included in the imaging analysis. The analysis can be carried out using classical approach [7] that is used in the thesis or by using the concept of 3D transfer function [8]. Probably the first approach would be sufficient since the system paraxiallity holds.

The chapter five investigates the performance of the developed soft X-ray microscope. The resolution is measured using Knife-edge test, where half-pitch spatial resolution of approx. 110nm is obtained. The other investigated parameter is a noise as effect of the exposure. The performance of build microscope is illustrated by set of taken images of technical and biological samples captured for different Field of View. There are examples of images of nanorods, polystyrene balls and images of dried biological sample – Chrysodidymus.

The thesis is finished with Conclusion and Future works chapter six.

Despite of the above remarks I believe that Muhammad Fahad Nawaz PhD thesis presents a solution of high scientific and technical level. Some results were published in three journal publications and the most important publication is, as presumed, in review process. Number of citations by the database Web of Knowledge is 31 and the Hirsch index 3. A significant number of citations of published publications provides evidence of a high scientific level.

In my opinion the PhD thesis that was submitted for evaluation meets the requirements for the doctoral dissertations and deserves rights to be discussed and defended in public.