19th IMEKO TC10 Conference
“MACRO meets NANO in Measurement for Diagnostics, Optimization and Control”
Delft, The Netherlands, September 21–22, 2023

In situ calibration of numerical aperture in optical microscopes

Poul-Erik Hansen[1], Lauryna Siaudinytė[2] and Thomas Siefke[3]

[1] *DFM - Danish National Metrology Institute, Hørsholm, Denmark, peh@dfm.dk*
[2] *VSL National Metrology Institute, Delft, The Netherlands*
[3] *Friedrich Schiller University Jena, Institute of Applied Physics, Jena, Germany*

***Abstract* – One of the most important components in microscopy is the illumination and imaging numerical aperture (NA). Together with the wavelength it sets the final limits and capabilities of the microscopy system. In scatterometry and ptychography a precise knowledge of the NA is required for the reconstruction algorithm. Here the uncertainty of values supplied by the manufactures are often to large, impairing the measurement capability of the system. In this research we demonstrate a method to measure the numerical aperture with high precision and thereby improve optical microscopy measurements.**

Keywords – Microscopy, Numerical aperture, uncertainty, back focal plane, Scatterometry, Industry, Innovation and Infrastructure

I. INTRODUCTION

Nanostructures have a wide array of applications in optics, diagnostics, food science, sensing, and process inspection monitoring. Some of these applications include enhancing waveguide coupling, improving linear encoders, making hyperspectral cameras, and printing color images. Imaging technologies like Optical Microscopy (OM), Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM) are the dominating quality assessment technologies in low volume, high-cost nanoscale manufacturing, whereas scatterometry and Mueller ellipsometry are the preferred technologies for high volume manufacturing. We propose to use confocal microscopy and microscope based scatterometry, with high NA objectives for shape reconstruction of nanostructures. These techniques can measure much smaller metrology target areas than the non-imaging technologies, which have a typical spot size limit of 30 μm. State of the art high NA objectives give excellent angular information and offers broadband wavelength transmission (UV to NIR). However, the measurement accuracy for all the microscope-based technologies depends critically on the calibration of the NA.
In scatterometry and ptychography, the numerical aperture of the microscope objective directly influences the diffraction pattern - the measurement result which is compared to the numerical simulations generated by solving Maxwell’s equations with rigorous coupled wave analysis (RCWA) or finite element method-based software [1, 2]. Since information about the microscope objective, the wavelength and nominal sample parameters are part of the apriori knowledge for diffraction pattern simulations, it is therefore crucial to know these parameters as precisely as possible. Furthermore, one can modify the spot size by alternating the numerical aperture making high numerical apertures very beneficial for measurement of small feature sizes.

II. SAMPLES AND EXPERIMENTAL METHODS

The combined confocal microscopy and scatterometry setup in Figure 1 was designed to beat the resolution limit and measure subwavelength periodic nanostructures. By using principles of the confocal microscopy, the unique diffraction signature is obtained on a CCD detector placed in the back focal plane/exit pupil of one arm and the image is obtained on the camera in the other arm. The back focal plane image shows the angular diffraction pattern within the NA of the objective. As an example, the shown back focal image in Figure 1 is for a one-dimensional grating with a pitch of 589 nm, an illumination wavelength of 635 nm and a nominal NA of 0.8. The back focal plane image is seen to be consisting of three regions, a dark central region and two brighter off-center regions. These borderlines between these regions are called Rayleigh lines. During a measurement, the light is focused on the sample by the microscope objective. After interacting with the periodic structure, the light diffracted and the diffraction orders after interfering with each other formed a diffraction pattern which in reflection mode was directed back to the microscope objective and later captured by the CCD camera (see Fig. 1). As mentioned above, the lines separating the diffraction orders (the Rayleigh lines) appear because of the diffraction principle and are highly dependent on the used wavelength and the periodicity of

the measured structure [3]. Therefore, the position of these lines can be used to calibrate the NA of an objective, since the provided dependency is well known. The Rayleigh line determination procedure is explained further in the next section of this paper. In order to perform the calibration, a 1D silicon line grating reference sample has been manufactured using electron beam lithography. Electron beam lithography is the technique that allows to achieve the high requirements for pitch and sample geometry. During the electron beam lithography process the sample is first cleaned with piranha solution, rinsed with DI water and mega-sonic agitation and then in ammonia water. Next, the natural oxide is removed by ion beam etching, then 20 nm of chromium is deposited on a silicon wafer without exposing the sample to air. The chromium layer will later be used as a hard mask. An e-beam sensitive resist is then applied and patterned using cell projection e-beam lithography [4]. In cell projection e-beam lithography, a reticle is introduced into the e-beam optical system. This reticle contains apertures that resemble a magnified part of the desired structure, e.g. an array of pillars. This allows larger areas of several microns to be exposed in a single shot, reducing writing time by an order of magnitude. This allows large, patterned areas to be produced efficiently, yet with sufficient flexibility and to take advantage of the typical ability of e-beam lithography to produce structures with dimensions down to tens of nanometers. For example, a 100mm x 100mm could be produced in about 6h using the process described here. The resulting pattern is transferred to the chromium layer by ion beam etching. The silicon is then etched against this hard mask using inductively coupled plasma etching. Finally, the remaining chromium is removed by wet etching in a solution of ceric ammonium nitrate and perchloric acid with megasonic agitation. The resulting structure was measured by traceable AFM and Mueller ellipsometry. The pitch and the geometrical parameters were found to be: pitch 500 nm, height of 307 nm, linewidth of 268 nm and sidewall angle of 90º.

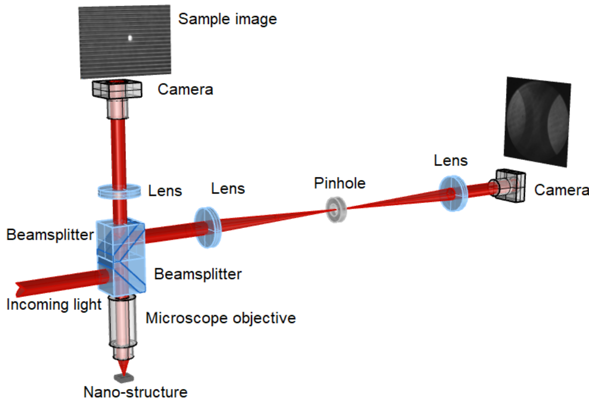

Figure 1. Layout of the combined scatterometry and microscopy setup

For the experiment in this article the wavelength was 488 nm and the microscope were equipped with infinity corrected microscope objective Mitutoyo with numerical aperture NA=0.55 and magnification of 50x.

III. DISCUSION AND ANALYSIS

The edges of the diffraction orders form Rayleigh lines and are a part of the diffraction pattern. Here we show that the measured diffraction pattern may be calculated from the knowledge of the wavelength of light, the sample period, and the numerical aperture of the microscope objective. The analysis is most easily carried out in Fourier space, so we start by introducing the Floquet theory for conical diffraction [1].

$$\alpha_m = n_I sin(\theta)cos(\varphi) - \frac{m\lambda_0}{\Lambda_x} = n_I\alpha_0 - \frac{m\lambda_0}{n_I\Lambda_x}$$
$$\beta = n_I sin(\theta)sin(\varphi) \qquad (1)$$
$$\gamma_m = \begin{cases} \sqrt{n_I^2 - \alpha_m^2 - \beta^2} & n_I > \sqrt{\alpha_m^2 + \beta^2} \\ -j\sqrt{\alpha_m^2 + \beta^2 - n_I^2} & n_I < \sqrt{\alpha_m^2 + \beta^2} \end{cases}$$

The size of the back focal plane image is the NA of the of the objective in the Fourier space (α, β, γ). The condition for Rayleigh lines may be found by setting $\gamma_m = 0$ in Eq. 1 and we obtain expression for circles that are shifted $\left({}^{m\lambda_0}/_{(n_I\Lambda_x)}, 0 \right)$ from the center of the measured NA disk. The radius of the shifted circle is the NA. If only zero and +/- first order diffraction is detected, we have three regions as shown in Figure 1. Mathematically this is formulated in the following equation.

$$\alpha_m^2 + \beta^2 = \left(\alpha_0 - \frac{m\lambda_0}{n_I\Lambda_x}\right)^2 + \beta^2 = 1 \qquad (2)$$
$$\alpha_0^2 + \beta^2 = NA^2$$

The Rayleigh lines can now be determined by applying the following procedure:

1. Place the center of the circles at $\left({}^{m\lambda_0}/_{(n_I\Lambda_x)}, 0 \right)$ for m=0, ±1, … .
2. Set the NA of the microscope objective to the value provided by the manufacturer.
3. Plot the experimental diffraction efficiency image and draw the rim of the diffraction circles by using the input from step 1 and 2.
4. Find the crossing points, (x_{cross}, y_{cross}), between the NA rim and the diffraction orders in the experimental

image and do a least square fit to get the initial NA estimate.

5. Ensure that the points (x_{cross}, y_{cross}) are points on the NA rim. To do this we use the fact that crossing points between the Rayleigh lines and the NA rim are given by $\alpha_0 = {m\lambda_0}/{(2n_l\Lambda_x)}$ and $\beta = \pm\sqrt{NA^2 - \alpha_0^2}$.
6. Next, we determine the microscope NA value as the NA value that gives the minimum distance between (α_0, β) and (x_{cross}, y_{cross}).

Figure 2 shows the result of such an analysis. As we can see from the results displayed in Fig. 2, the NA values differ.

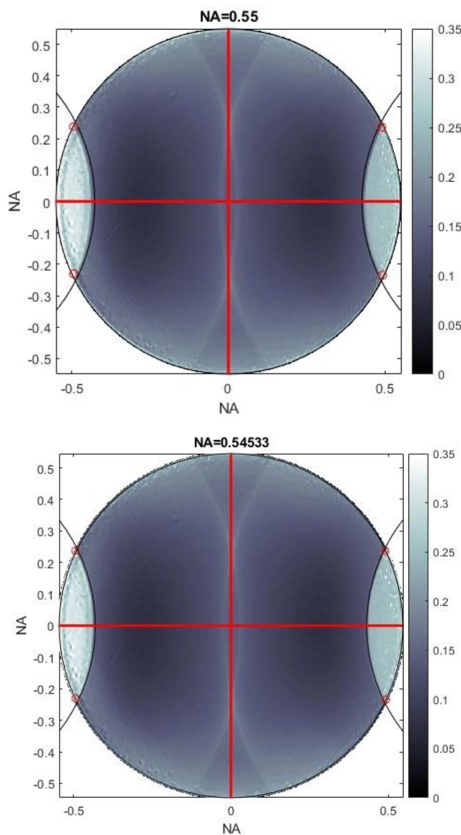

Figure 2. Comparison of the nominal NA and numerically calibrated NA of Mitutoyo microscope objective. The top image is obtained using the manufacture's NA value, whereas the bottom image is obtained using the presented method. The red circles in the figures are the crossing points (x_{cross}, y_{cross}).

A wrong numerical aperture directly affects scatterometry since the reconstruction is done by comparing diffraction efficiencies in the back focal plane. It is needless to say that if one compares diffraction efficiencies for different pixel locations one will get wrong results. A wrong numerical aperture also affects the observed image on the camera as may be seen from the fact that the Debye/angular spectrum integral is performed over the entire NA disk [5]. Once the microscope objective is calibrated, it may be used to measure the optical pitch of the grating and thus reduce the number of fitting parameters in scatterometry.

IV. CONCLUSIONS AND OUTLOOK

We report on the first result of a new numerical aperture calibration method. As presented in the experimental part of the research, the NA value provided by the microscope objective manufacturer might differ from the actual NA value. Since NA calibration plays a crucial role in scatterometry where NA affects the measurement results, it is important to ensure the value with the highest precision. Calibration of the NA provides an additional benefit of reducing the number of parameters to be reconstructed in scatterometry.

The method presented in this paper is attractive, since it does not require an external setup but calibrates the objective within the microscope and it is simple to implement. The only requirements are a traceable standard, a Bertram lens placed in the optical path for turning the image plane of the microscope into the back focal plane and a bandpass filter. Furthermore, we will in a forthcoming article show that the method is easily generalized to two dimensional periodic structures, which will give more crossing points and hence higher precision in the determination of the NA.

V. ACKNOWLEDGMENTS

This project (20IND04 ATMOC and 20FUN02 POLight) has received funding from the EMPIR program co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation program.

REFERENCES

[1] Madsen, M. H., Hansen, P-E.:Scatterometry—fast and robust measurements of nano-textured surfaces, *Surf. Topogr.: Metrol. Prop. 4 023003 (2016)*

[2] Hammerschmidt M., Zschiedrich, L., Siaudinyté, L., Manley, P., Schneider, P. and Sven Burger "Forward simulation of coherent beams on grating structures for coherent scatterometry", Proc. SPIE PC12619, Modeling Aspects in Optical Metrology IX;

[3] Model, R., Rathsfeld, A., Gross, H., Wurm, M., Bodermann, B. A scatterometry inverse problem in optical mask metrology.Journal of Physics: Conference Series 135 (2008) 012071 doi:10.1088/1742-6596/135/1/012071.

[4] Hädrich, M., Siefke, T., Banasch, M. and Zeitner, U.D. (2022), Optical metasurfaces made by cell projection lithography. PhotonicsViews, 19: 28-31. https://doi.org/10.1002/phvs.202200036

[5] Çapoğlu, l R., Rogers, J. D., Taflove, A., Backman, V.: The Microscope in a Computer: Image Synthesis from Three-Dimensional Full-Vector Solutions of Maxwell's Equations at the Nanometer Scale. *Progress in Optics, Elsevier, Volume 57, 2012.*