[BayesOM] Bayesian inference in optical metrology

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The semiconductor industry is a key element of contemporary developments in science and technology. Metrology plays a pivotal role in successful manufacturing. Optical metrology techniques are of vital interest because they provide a noninvasive means for precise and fast measurements with nanoscale accuracy. Scanning-free methods, such as full-field interferometry, are of crucial importance because they enable simultaneous widefield measurements. Information regarding the semiconductor element geometry and refractive index distribution is encoded in the phase term of the generated interferometric fringe pattern. The central aspect of this optical metrology technique is the demodulation of the phase map from the recorded intensity distribution. Fringe pattern analysis methods are under constant development as increasingly challenging conditions, such as additive manufacturing, impose stringent metrological requirements. The most popular and reliable phase-demodulation technique is based on recording three or more phase-shifted interferograms. This creates the need for a precise phase-shifting module in the interferometer, which makes it more complicated and costly. Moreover, the phase demodulation procedure via fringe pattern phase-shifting increases the measurement process. The accuracy of the technique depends on the precision of phase shifting, the quality of recorded fringe patterns (signal-to-noise ratio), and the phase demodulation algorithm itself. A general limitation of phase-step detection relates to the pixel-size displacement of the fringes. Additionally, the location of the abrupt height change is full of phase errors, especially those augmented by coherent noise.

In the proposed [BayesOM] project, we explore a novel algorithmic concept for phase demodulation in a single shot (using a single interference pattern). To date, single-shot phase demodulation algorithms have used Fourier, Hilbert, or wavelet transforms and were constrained in terms of ill-posed problems and strong errors, especially in the area of abrupt height change of the measured step-like object, for example, waveguide structure (low-pass filtering of the phase step and strong phase noise). To the best of our knowledge, our novel idea is to employ Bayesian inference for optical metrology. We will study how different Bayesian models can be deployed for the estimation of posteriors, where we will encode parameters of the geometry of the studied waveguide structures (height, width, tilt, inclination, etc.). Initial studies show that we can easily achieve sub-pixel heigh profile variation sensitivity, which, in combination with 405 nm violet laser illumination and Twyman-Green or Linnik-type interferometric setup, could yield first-of-a-kind Angstrom level optical full-field measurement sensitivity and precision. We will study different models under varying simulated and experimental conditions, considering different objects (shapes, reflectivity, step height values, etc.), fringe noise and contrast levels (coherent sensing and partially coherent illumination sources), and additional numerical algorithms for noise minimization and fringe contrast augmentation.

Planned innovations are especially important in semiconductor metrology, highlighting possible applications in waveguide measurements crucial in on-chip fluorescent nanoscopy developed by Professor Balpreet Ahluwalia's group at The Arctic University of Norway (Tromso). Basic research is needed to assess the extent to which Bayesian inference can be employed in optical metrology for phase-map statistical estimation. PhD student is envisioned to spend 6 months in Professor Ahluwalia lab in Tromso mastering waveguide optical measurement procedures and implementing Bayesian inference. The Ahluwalia group pioneered the development of optical on-chip fluorescence nanoscopy technology, where waveguides are innovatively used to illuminate samples under evanescent wave regimes, and their fast and reliable measurements are of pivotal importance. We will also cooperate with Dr. Maciek Wielgus from the Max Planck Institute for Radio Astronomy, Bonn, Germany, one of the main researchers in the Black Hole Initiative Event Horizon Telescope. He developed Bayesian inference-based algorithm techniques for estimating black hole parameters from radioastronomical data. Thus, we plan to build on this success on an astronomical scale and transfer it into novel solutions in angstrom-sensitive widefield optical metrology for semiconductor quality control.