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Coordinate interferometric measurement with infrared telecom laser diode

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Abstract
We present the design of an interferometric position measuring system for the control of the sample-carrying translation stage in an e-beam writer with reproducibility of the position on nanometre level and resolution below nanometre. We introduced differential configuration of the interferometer where the position is measured with respect to a central reference point to eliminate deformations caused by thermal and pressure effects on the vacuum chamber. The reference is here the electron gun of the writer. The interferometer is designed to operate at infrared telecommunication wavelength due to the risk of interference of stray light with sensitive photodetectors in the chamber. The laser source used is a narrow-linewidth DFB laser diode with a custom-developed electronics that allows for high precision and stability of the laser diode chip temperature and the injection current, very low-noise, EMI protection and high-frequency modulation capability. Detection of the interferometric signal relies on a technique using a high frequency modulation of the laser's optical frequency and the single-detector phase-sensitive detection.

Keywords: nanometrology, interferometry, position sensing

1. Introduction

The electron beam microscopy and lithography (the latter known as the e-beam writing) are well-established techniques which achieve significantly better resolutions than the methods relying on visible light. The electron microscopy is primarily an imaging technique that could be eventually combined with analytical tools such as a geometrical measurement on the samples. In such a case the scanning subsystem has to be combined with precise positioning and displacement measurement of the translation stage that carries the samples. Analogously the deposition in the e-beam writing requires precise coordination of the deposition system and the substrate (typically a semiconductor wafer). In both cases the precision of the positioning system have to be better than the finesse of the scanned or deposited structures.

We proposed a coordinate measuring system based on a laser interferometry with that operates in two degrees of freedom that tracks the position of a 2D translation stage within the vacuum chamber of the e-beam writer. The system is required to achieve a one-nanometre level precision on the travel range that will cover the typical size of a semiconductor wafer with translation speed 10 mm/s. The system uses a single frequency laser operating in the infrared telecom wavelength band in order to avoid interference of the stray light with the sensitive scintillators inside the vacuum chamber.

The optical system is designed as four-pass differential arrangement where the relative position of the translation stage with respect to the e-beam source above the sample is measured so that the influence of the shape deformations of the whole vacuum chamber and instrument frame is minimized. The single-detector homodyne detection technique relies on a high-frequency modulation method that combines the digital signal processing and the analogue front end with phase detectors, which generate quadrature sine/cosine signals.

2. Laser source

The laser system was based on a single-frequency narrow-linewidth DFB semiconductor laser diode operating at the telecommunication wavelength of 1550 nm – this wavelength band meets the condition to avoid radiations on the visible wavelengths inside the chamber and also enables the use of generally available fibre-optic components. We used a custom electronics for precise stabilization of the principal operational parameters of the laser diode (see Fig. 1), i.e. the injection current and the chip temperature. The temperature controller provides wide-range temperature tuning and the thermal stabilization servo loop. The injection current is supplied by the low noise current source that offers a low-frequency DC-coupled injection current modulation and tuning option as well as the high-frequency modulation by additional signal component superimposed to the injection current via a high-frequency transformer [1].

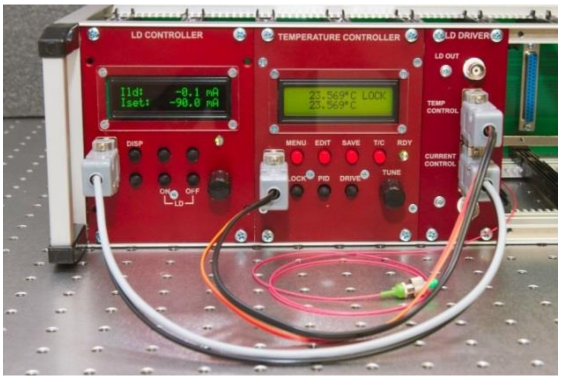

Figure 1. Laser diode control electronics: left to right are the current source with current controller, the temperature controller and the diode housing.

The stability of the laser optical frequency relies on the stability of the laser diode injection current and the diode chip temperature. Investigation of the long-term drifts will indicate whether the further stabilization of the optical frequency will be necessary. The setup can be easily enhanced by adding an acetylene-filled gas cell and implementing simple linear spectroscopy setup.

3. Optical system of the interferometer

The optical arrangement is four-pass differential, with two beams in both the reference and measurement arm. It is based on the Michelson interferometer setup with cube-corner retroreflectors in the beam paths for the compensation of small tilt errors of the positioning stage, polarization separation of the reference and measurement beam. The polarization-maintaining fibre in conjunction with the fused PM fibre splitter is used for beam delivery into the two measurement axes.

The differential arrangement is used for measuring the relative displacement between the coordinate translation stage and the e-beam source body frame. The individual parts of entire measurement system was tested using several consecutively built testbed setups (see Fig. 2) that were put together for preliminary validation and further design and optimizations of the mechanical setups and identification of the degrees of freedom that are optimal for adjustment.

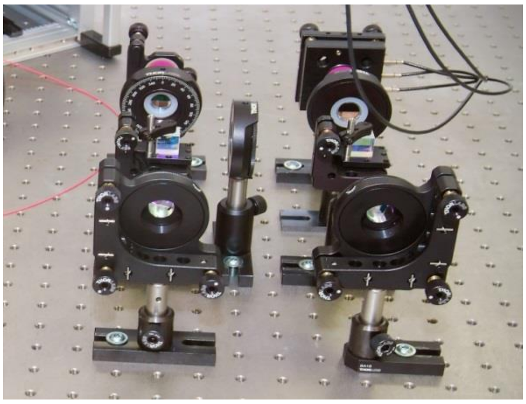

Figure 2. The interferometric testbed setup.

4. Detection system

In order to avoid the complex optics necessary for the homodyne detection (that would have to by designed and adjusted for the infrared wavelength) or the need for two-frequency laser for the heterodyne system we use a single detector homodyne detection scheme [2-4]. This technique also exploits the key advantage of a telecom laser diode – the possibility of high frequency modulation (over 5MHz to meet the velocity requirement). The quadrature sine/cosine signal, that represents the rotating phase vector, is generated using a phase-sensitive derivative detection. To follow the needed frequency bandwidth we based the front-end of the detection electronics on analogue circuitry in conjunction with high-frequency mixers (future development will focus on programmable hardware structures – e.g. FPGAs).

The varying optical path difference between the reference and measuring path of the interferometer (we need up to 6" travel range, referring to the wafer size) produce varying imbalance between the sine and cosine signal amplitude. We addressed this issue by incorporating the adaptive gain control in one of the channels. The schematic of the detection chain for one measuring axis is shown in Fig. 3.

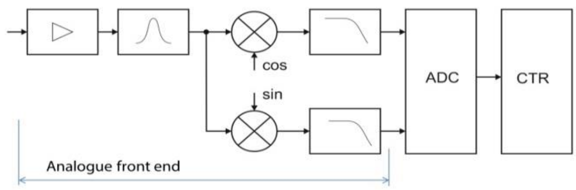

Figure 3. Block diagram of the modulation-based interferometer signal detection.

5. Preliminary tests

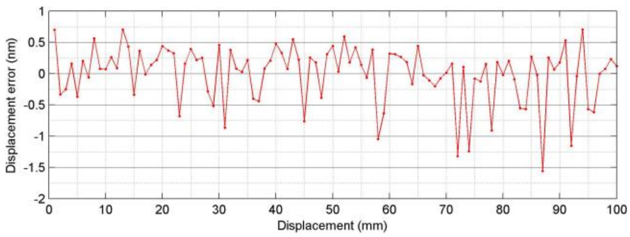

Figure 4. Preliminary displacement error measurement.

Within the preliminary experiments we investigated the displacement measurement accuracy of our system on a testbed rig equipped with a 100mm translation stage and two separate interferometric detection systems with shared laser source and beam paths. Our system was tested against the reference four-detector homodyne detection. The results showed that the displacement accuracy fits to the required nanometer range. Proper validation will be carried out on the e-beam writer prototype that is currently being completed.

6. Conclusion

We designed a coordinate measuring system, based on laser interferometry, for positioning of the translation stage for e-beam writer. The design includes the coherent laser source with modulation capabilities, optical arrangement of the interferometer and the detection system. The design exploits experience we gained within participation in the EU funded EMRP REG1 IND58 6DoF project. The system, developed in cooperation with a leading producer of the electron optics and instrumentation (also based in Brno, CZ) it represents a significant applied research effort that is oriented to introduction of laser interferometry into industrial e-beam devices.

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