Proceedings Symposium IEEE/LEOS Benelux Chapter, 2000, Delft, The Netherlands

Measuring absolute optical path differences with angstrom accuracy over ranges of millimeters

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For the figure measurement of mirrors to be used in extreme-ultraviolet lithography, we develop a novel method to measure absolute optical path differences (OPD) with 0.1 nm accuracy over ranges of several millimeters. The method combines two different measurement techniques: frequency modulation to determine the absolute OPD with an accuracy of about half a wavelength and heterodyning to determine the OPD modulo one wavelength with an accuracy of 0.1 nm. By combining the results of the two methods, the absolute OPD is determined with the large range of the frequency modulation and the high accuracy of the heterodyning. The setup and measurement results of the heterodyning method are presented.

1. Introduction

Our long-term objective is the development of a two-beam visible-light interferometer to measure the figure of the aspherical mirror substrates that will be used in the projection systems for extreme-ultraviolet lithography (EUVL). This interferometer was described in [1]. An essential component of this interferometer is a two-dimensional detector array with accompanying electronics for the measurement of the absolute optical path difference (OPD) between the reference and object beams at each detector.

For this particular application, the OPD has to be measured with an accuracy of 0.1 nm, whereas the measurement range should stretch from 0 to circa 3 mm. Because no single measurement method can measure an OPD over a range of 3 mm with an accuracy of 0.1 nm, we use a combination of two methods. The first method is used to measure the OPD modulo λ with the required accuracy. This method is often called heterodyning [2], but we will refer to it as phase modulation (PM), to distinguish it from the second method, frequency modulation (FM) [3]. The latter is used to determine, within the required range, the integer multiple of λ of the OPD. The OPD is computed by summing the OPD modulo λ, measured by the PM method, and the integer multiple of λ within the OPD, measured by the FM method. In order to be able to determine the integer multiple of λ of the OPD, the accuracy of the FM method should be $\lambda/2$ or better, which is circa 0.3 µm at the measurement wavelength of 633 nm.

The first steps in the development of the interferometer with the two-dimensional detector array, is the development of (i) a subsystem with a single detector to demonstrate that the accuracy of the PM technique can be as high as 0.1 nm, and (ii) a subsystem with a single detector to demonstrate that the accuracy of the FM technique can be as high as 0.3 µm. The setup of the FM subsystem has been described in [1]. This paper describes the setup and measurement results of the PM subsystem.

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2. Phase modulation subsystem

The PM subsystem that we use distinguishes itself from existing PM systems in the way it measures the phase difference. Therefore, this description focuses mainly on that phase measurement.

The setup of the PM subsystem is shown in Fig. 1. The laser, a HeNe laser with a wavelength of 633 nm (corresponding to a frequency of 470 THz), is stabilized in frequency. The phase ϕ of the laser beam, as a function of the time t, is depicted by the first graph. The laser beam is directed to an acousto optical modulator (AOM), which functions as a frequency shifter. The zeroth and first order beams of the AOM are referred to as the object (gray) and reference (black) beams, respectively. The reference beam is shifted in frequency, while the object beam is not. Hence, the phase of the reference beam increases at a higher rate than the phase of the object beam, as illustrated in the second graph. The difference in these rates is the modulation frequency f_m of the AOM, which is 32 MHz.

Parts of the reference and object beams are led to the reference photodetector, while the other parts are led via the delay line to the object photodetector. The delay of the object beam in relation to the reference beam, introduced by the delay line, results in a shift $\Delta\phi$ of the phase of that object beam, as the third graph shows. With our delay line we can introduce arbitrary phase shift $\Delta\phi$ within a range of 4π, with an accuracy of 0.3 mrad (corresponding to an OPD range of two wavelengths and 0.03 nm accuracy).

At the object and reference photodetectors, the pairs of reference and object beams interfere. Due to the interference, the phase of the detector signals is equal to the phase

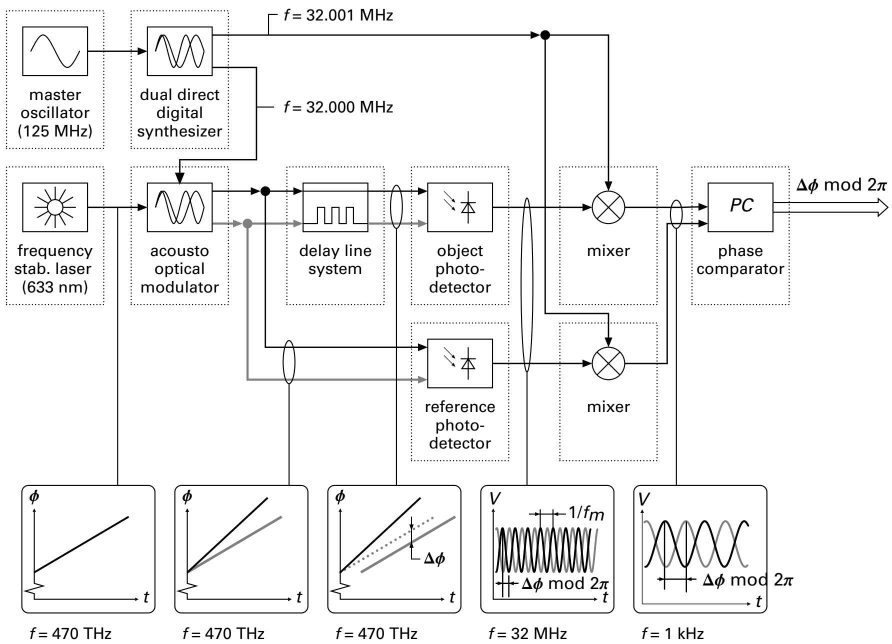

Fig. 1 Setup of the phase modulation subsystem.

difference between the interfering optical beams. Hence, the frequency of both detector signals is equal to the modulation frequency f_m and the phase difference between the two *electrical* detector signals is equal to the phase shift $\Delta\phi$ introduced by the delay line in the *optical* object beam. The two detector signals and the phase difference $\Delta\phi$ modulo 2π are depicted by the fourth graph.

We could directly determine $\Delta\phi$ modulo 2π by measuring the phase difference between the detector signals with a phase comparator, such as a time counter. The required OPD accuracy is 0.1 nm, which corresponds to a phase difference accuracy of 0.1 mrad, or a time delay accuracy of 5 ps at the detector signal frequency of 32 MHz. However, the resolution of even the most advanced time counters is circa 20 ps. Therefore, we mix the detector signals down from the frequency of 32 MHz to a frequency of 1 kHz with the components illustrated in Fig. 1. At this frequency of 1 kHz, the required 1 mrad phase difference accuracy corresponds to a time delay accuracy of 0.16 μs, hence a standard HP 53132A time counter can be used as phase comparator.

The master oscillator is a low-phase noise quartz crystal oscillator at 125 MHz. Two direct digital synthesizers, synchronized by the master oscillator, generate the input signal for the AOM at 32.000 MHz and the input signal for the mixers at 32.001 MHz. The phase noise introduced by the direct digital synthesizers and by the mixers is negligible in relation to the phase noise of the master oscillator.

3. Measurement results

The measurement results are shown in Fig. 2. The OPD introduced by the delay line, denoted by OPD_i, is varied step by step over two wavelengths (2×633 nm), with step

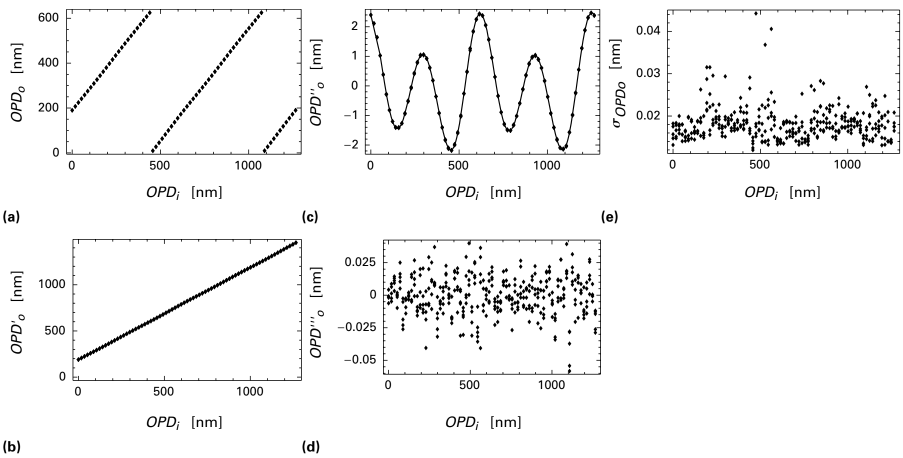

Fig. 2 Measurement results of the PM subsystem. (a) The measured OPD_o values as function of the OPD_i introduced by the delay line. (b) The OPD'_o values corrected for jumps of λ. (c) The deviations OPD''_o from the linear function fitted through the OPD'_o values. (d) The deviations OPD'''_o from the periodic function fitted through the OPD''_o values. (e) The standard deviations of the groups of measured OPD_o values.

sizes of 17.6 nm. At each step, the phase comparator measures the phase difference modulo 2π a large number of times: 5 times a group of 500 measurements is taken. The total measurement time is about 20 minutes.

Of each group of 500 measurements we compute the average and the standard deviation. These phase differences are converted into OPD values. Fig. 2(a) shows the averaged OPD values, denoted by OPD_o. Subsequently, the jumps of λ in the OPD_o values are removed. The result, denoted by OPD'_o, is shown in Fig. 2(b). After that, a linear function is fitted through the OPD'_o values, and subtracted from these values. Fig. 2(c) shows the resulting values, denoted by OPD''_o.

These values show a periodic variation, with a period equal to one wavelength. This phenomenon is well-known in heterodyne distance measurement and is caused by polarization cross-talk in the delay line that we developed especially for this single-detector system. Because our interferometer for figure measurement will not give rise to polarization cross-talk, we leave this phenomenon out of consideration. We correct for it by fitting a periodic function with period λ through the OPD''_o values and subtracting this function from the OPD''_o values. The result, denoted by OPD'''_o, is shown in Fig. 2(d). The standard deviations of the groups of 500 measurements are shown in Fig. 2(e). The OPD'''_o values, as well as the standard deviations, show that the measured OPD_o values deviate less than circa 50 pm from the OPD_i values introduced with the delay line, provided that we leave the polarization cross-talk out of consideration.

4. Conclusions

A phase modulation system for accurate OPD measurements was built and tested. The measurement results demonstrate the feasibility of using a PM system for the measurement of the OPD with an accuracy of 0.1 nm.

5. Acknowledgements

This work was supported by the Dutch Technology Foundation STW, by ASM Lithography, Veldhoven, The Netherlands, and by Carl Zeiss, Oberkochen, Germany.

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