Using Refraction in Thin Glass Plates for Optical Path Length Modulation in Low Coherence Interferometry

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Summary

In this publication we show that it is possible to replace expensive high–precision linear actuators in white–light–interferometers with inexpensive glass plates and a stepper motor. By rotating the glass plate in the reference beam its optical path length can be modulated and the interferogramm recorded as if a reference mirror was moved.

Introduction

A central part of all Michelson white–light–interferometers is the high–precision linear actuator used to control the length of either the measurement or the reference arm. This publication presents an alternative approach to this task by placing a glass window in the reference beam and tilting it. Due to refraction at the transition between air and glass the optical path length of light passing can be controlled precisely.

Fig 1. Michelson white–light–interferometer
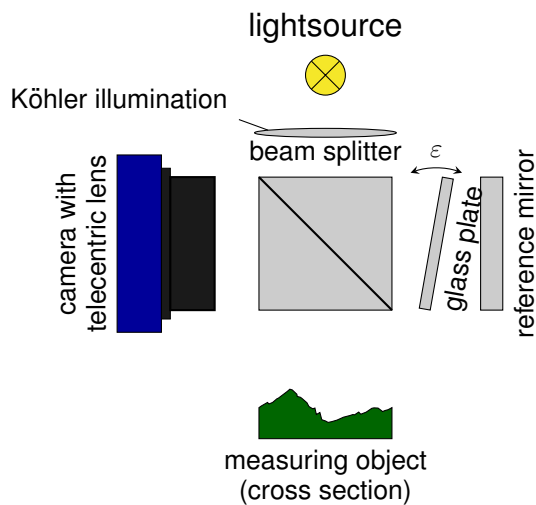
Theoretical considerations

The idea behind using a glass window to modulate the optical path length of the reference beam is based on the observation, that light passing through a plate of glass experiences optical path length changes due to the refraction of light when passing to a medium with a refractive index n different from air. The angle of refraction depends on the angle of incidence and the ratio of the different refractive indexes. Also, the optical path length varies with the refractive index of the medium. By controlling the angle of incidence it is, therefore, possible to control the parallel shift and the length of the beam within the glass plate.

By comparing the length l_G of the beam within the glass with the path l_L, see fig. 2, it would have taken without glass plate it is possible to identify an equation that describes the relation between angle of incidence and the change in optical path length. With the simplification that the refractive index of air $n_L = 1$, the equation can be written as

$$\Delta s = d \cdot \left(\sqrt{n_G^2 - \sin^2\left(\varepsilon_1\right)} - \cos\left(\varepsilon_1\right) \right) \tag{1}$$

and gives the change in optical path length relative to no glass in the reference arm. It can be used to calculate optical path lengths if the refractive index n_G of the glass is taken into consideration for the variation of inner–medium light speed.

Implementation

In order to use a glass plate to control the optical path length of the reference arm it is necessary to precisely control the angle of rotation ε of the plate. To achieve this, a stepper motor with a high ratio planetary gear box is used and the rotation transferred to the glass plate via a toothed belt. This results in a transmission ratio for motor angle to plate angle of $400:1$ and enables the positioning of the plate in increments of $0.0045°$. The mechanics have been designed to be free of backlash for the purpose of accuracy.

A challenge in using this system is however, that the change in optical path length is not a linear function of the rotational angle of the plate. This results in a non–equidistant recorded image stack for later reconstruction, which has to be considered in the analysis of the data. It was found that digitally resampling the recorded interferogramms is a suitable approach for robust evaluation of the interferogramm because the described setup allows for a high sampling rate of the interferogramm.
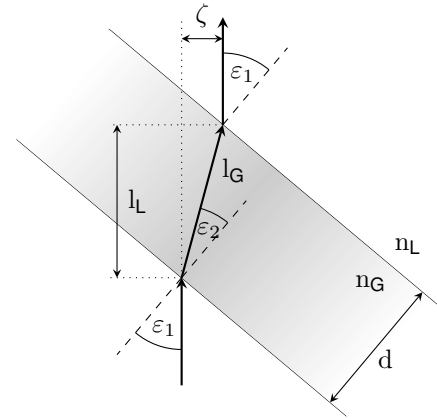

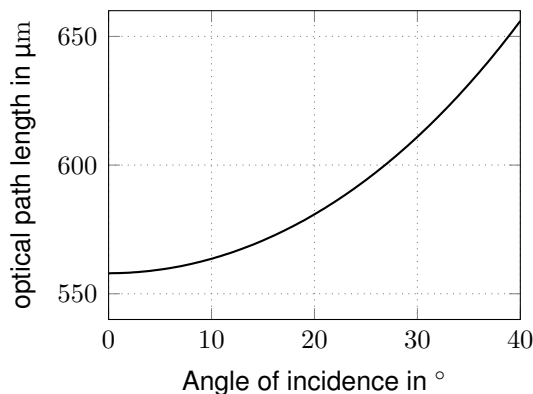Fig 2. Path of light beam when passing through a glass plate

Fig 3. Optical path length over angle of incidence (eq. 1)

Discussion

With the presented method, we were able to successfully measure the surface topology of several objects and compare the reconstructions to those of a commercial white–light–interferometer named "Veeco Wyko NT1100" with a vertical resolution of $3\,\mathrm{nm}$. While there is still room for improvement in terms of speed (recording of raw data takes between 20 to $70\,\mathrm{min}$ and reconstruction 30 to $170\,\mathrm{min}$ depending on surface height) the novel approach modulation of the optical path length was a success. By using hardware with a value of about $100\,€$ it was possible to replace the commonly used, and far more expensive, high–precision linear actuators.