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Simultaneous Measurement of Thickness and Refractive Index by Chromatic Confocal Coherence Tomography (CCCT)

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Abstract:
One of the main problems for optical inspection in precision manufacturing is to handle unknown layers on the specimen correctly, especially to achieve the goal of high-resolution topography measurement of underlying surfaces without prior cleaning. We introduce a new hybrid scheme for simultaneous measurement of thickness and refractive index of layered specimens. Confocal systems underestimate the layer's thickness depending on the refractive index, while interferometers evaluate the optical path length, which is an overestimation due to the refractive index of the material. By a combination of a chromatic confocal and an interferometric channel, it is possible to measure topography trough contamination layers without prior knowledge in a single shot. In this contribution, theoretic background and evaluation strategies are discussed as well as the possible range of applications.

Key words: Chromatic Confocal, Spectral Interference, Metrology, Topography, Multi-layer measurement

Introduction

In precision manufacturing, the workpiece usually has to be cleaned before inspection, since contaminations like machining fluids distort the measurement of the specimen's topography, especially if an unknown refractive index of the contamination layer cannot be corrected for. There are some systems reported to enable simultaneous measurement of a layer's refractive index and thickness without prior knowledge, mostly based on white light interferometry, (chromatic) confocal microscopy and/or spectral interferometry [1-12]. However, all of them either lack single-shot capability, require transparent specimen or sophisticated signal modelling or use very complex experimental setups. We propose a new method, which is capable of simultaneous measurement of refractive index and layer thickness. Thus, high-resolution topography measurements can be corrected even in the case of unknown layers atop. Hence the physical situation is very similar, we also aim for specimen carrying varnishes/coatings or thin materials as samples. The single-shot capability seems to be important especially for liquid layers. The experimental setup presented here is a point sensor that can be extended to a line sensor or maybe even an area sensor by the same means applicable to other principles featuring single-shot spectral detection.

Measurement Principle

The measured thickness of refractive media may deviate systematically from the geometric value depending on the used physical principle. Interferometric methods for instance actually measure Optical Path Differences (OPD), therefore the measured quantity d_{int} is an overestimation of the geometric thickness d by the refractive index n:

$$d_{int} = n \cdot d \tag{1}$$

Confocal schemes, on the other hand, are mainly distorted by the refraction at surfaces, where n changes. Fig. 1 depicts, how a confocal measurement system previously calibrated in air assumes a specimen under a semi-transparent layer at a raised position.

Using the numerical aperture $NA = n_1 \cdot sin(\alpha) = n_2 \cdot \sin(\beta)$ and simple geometric considerations, the confocally measured thickness d_{conf} calculates to

$$d_{conf} \overset{n_1=1}{=} \frac{d}{n_2} \cdot \frac{\sqrt{1-NA^2}}{\sqrt{1-\left(\frac{NA}{n_2}\right)^2}}. \tag{2}$$

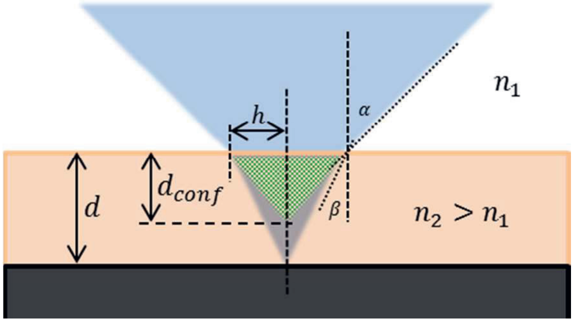

Fig. 1. Confocal underestimation of the layer thickness due to refraction at the upper surface.

Given an independent measurement of both pieces of information, d_{int} and d_{conf}, a combination of eq. (1) and (2) gaines a polynomial of fourth order, containing the combined measured thickness d_{comb} only in the power of four and two. Hence, there is one real valued positive solution:

$$d_{comb} = \sqrt{\frac{NA^2 \cdot d_{conf}^2 - \sqrt{NA^4 \cdot d_{conf}^4 + 4 \cdot (1-NA^2) \cdot d_{int}^2 \cdot d_{conf}^2}}{-2 \cdot (1-NA^2)}} \quad (3)$$

We should note that this solution neglects that in the case of broadband illumination the refractive index of eq. (1) will be the group refractive index, whereas eq. (2) uses the phase index. This will give rise to systematic errors depending on the used light source.

Chromatic Confocal Coherence Tomography

Over the last years, Chromatic Confocal Spectral Interferometry (CCSI) was studied as a single-shot high-resolution topography measurement system [13-16]. It consists of a Chromatic Confocal (CCM) scheme with an additional reference arm, hence combining the large measurement range at a still high lateral resolution of CCM with the very high axial resolution of Spectral Interferometry (SI). The system provides two decoupled information channels, an interferometric and a confocal one. Thus, the experimental setup of CCSI is also of use to assess the problems discussed above. The lab demonstrator is shown in Fig. 2: A SLD (810..870 nm) and spectrometer detector are fibre coupled to the sensor head, where the fibre's core acts as a confocal filter. Near the back focal plane of the microscope objective in the object arm, a refraction compensated Diffractive Optical Element (DOE) introduces chromatically separated foci in the measurement volume, while the reference arm is built achromatically. Using a set of 20x 0.46 Objectives (Olympus LMPlanFl), a single-shot measurement range of about 100µm is reached.

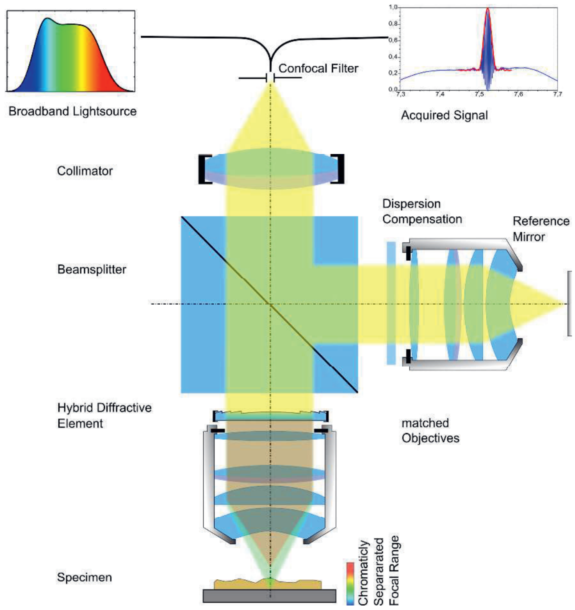

Fig. 2. Scheme of CCSI/CCCT lab setup.

Signal and Evaluation

The CCCT signal acquired by the spectrometer basically consists of a superposition of multiple CCSI signals. Here, only specimens consisting of two surfaces are considered without loss of generality. As shown in Fig. 3, each surface provides a strong confocal peak with an underlying frequency corresponding to its OPD with respect to the reference mirror.

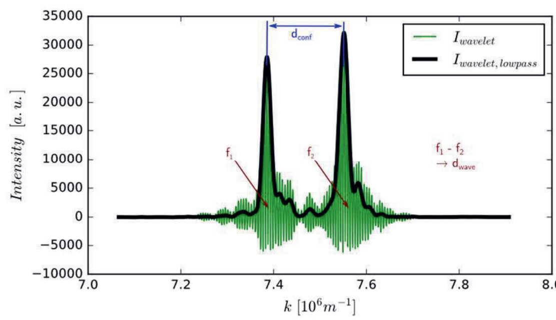

Fig. 3. Experimental signal from a diamond sample of 100µm thickness after the subtraction of the reference signal.

For evaluation of d_{conf}, the distance between the centres of gravity (COG) of the peaks' upper halves are calculated. The interferometric evaluation is carried out for each peak separately, as they are strongly dominated by their respective frequency. After fourier transform, the COG difference gives d_{int}.

System Parameters

The parameters of the CCCT setup are mainly dominated by the NA of the used microscope objective. In the confocal channel, the peaks' width mainly depends on the NA, thus the positional resolution for each surface (~1/50 FWHM). Also, the minimal measurable thickness is limited by the minimal distinguishable peak distance, hence the confocal peak width. Although the interferometric channel provides less uncertainty and the solution described in eq. (3) is not severely affected by imperfect measurements from the different channels, the overall uncertainty is basically limited to the one of the confocal channel.

Conclusion and Outlook

Based on the topography measurement system CCSI, a new scheme named CCCT was introduced, which is capable of simultaneous single-shot acquisition of refractive index and layer thickness. Thus, a corrected topography measurement is possible, even if the specimen is covered by an unknown layer, e.g. machining fluids. In future work, a detailed modelling of the signal is planned in order to reduce measurement uncertainties by a fitting procedure. Also, to achieve a real 2D multi-layer topography measurement, a careful modelling of the actual measurement positions may be needed, as local curvatures of each surface act as optical elements.

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