THIN FILM EXTRACTION FROM SCANNING WHITE LIGHT INTERFEROMETRY

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INTRODUCTION

Scanning white light interferometry (SWLI) is now an established technique for the measurement of surface topography. It has the capability of combining sub-nanometre interferometric resolution with a range limited only by the z-traverse, typically at least 100µm. A very useful extension to its capability is the ability to measure thin films on a local scale. For films with thicknesses in excess of ~2µm (depending on refractive index), the SWLI interaction with the film leads simply the formation of two localised fringe bunches, each corresponding to a surface interface. It is evidently relatively trivial to locate the positions of these two envelope maxima and therefore determine the film thickness, assuming the refractive index is known. For thin films (with thicknesses ~20nm to ~2µm, again depending on the index), the SWLI interaction leads to the formation of a single interference maxima. In this context, it is appropriate to describe the thin film structure in terms of optical admittances; it is this regime that is addressed through the introduction of a new function, the 'helical conjugate field' (HCF) function. This function may be considered as providing a 'signature' of the multilayer measured so that through optimization, the thin film multilayer may be determined on a local scale. Following the definition of the HCF function, examples of extracted multilayer structures are presented. This is followed by a discussion of the minimum film thickness limit of the approach.

Conventionally, thin film structures are measured using either a spectrophotometer or an ellipsometer. For large-area vacuum deposited thin films (single or multi-layer), such measurement approaches are very appropriate. In a different arena, SWLI is now an established technique for the measurement of surface topography. Typically, SWLI instruments provide a sub-micron lateral resolution (determined by the numerical aperture of the objective) and a sub-nanometre interferometric z-resolution. Within the MEMS/MOEMS industries, there is a growing requirement for the ability to measure thin film structures that only exist on a local scale. Through the development of the HCF function, the local topography capability of SWLI may be extended to include the determination of layer thicknesses and dispersive indices. An additional benefit is that, through the knowledge of the thin film structure, the phase-change on reflection (PCOR) may be compensated so that 'true' step-heights may be obtained.

Results of both single and multi-layer thin film extraction on a local scale from SWLI measurements are presented. The effectiveness of PCOR-compensation in terms of the associated step-heights at the films' boundaries is then shown.

It is useful to summarise the limits of this approach. Firstly as the thickness of a thin film decreases, the distortion of the helix reduces and so the 'signature' of the thin film structure becomes progressively featureless over the HCF bandwidth; the limit (for a thin film index ~2.2 on a BK7 substrate) is ~20nm. At the 'thick thin film' end, the single interference maximum gradually divides into two interference maxima. The multiple cavity reflections (that for thin films give rise to the standing wave electrical field pattern within the film structure) become progressively integrated out; for a single layer, the HCF function becomes progressively dominated by the sinusoidal term corresponding to the electrical fields reflected off the front and rear film surfaces. Depending on the index, this limit corresponds to a film thickness ~ 2µm.

ANALYSIS

It may be shown that through performing SWLI measurements on a thin film coated substrate (single or multi-layer) together with a 'reference' substrate, such as the glass BK7, it is possible to construct the HCF function [1]. This is defined as the product of the conjugate of the net electrical field reflectance from the 'reference' together with the thin-film/'reference' quotient of the Fourier transform positive frequency sidebands corresponding to the series of SWLI intensity values surrounding the zero path difference :

$$\mathrm{HCF}(\nu) = \bar{\mathrm{r}}^{*}_{\mathrm{sub}}(\nu)\left(\frac{\Im(\mathrm{I}_{\mathrm{sfilm}}(\bar{\mathrm{z}}))_{\mathrm{SB+}}}{\Im(\mathrm{I}_{\mathrm{sub}}(\bar{\mathrm{z}}))_{\mathrm{SB+}}}\right)\text{...........}\ (1)$$

The HCF function may therefore be determined over a range of frequencies (typically corresponding to ~480nm to ~720nm). within the two original Fourier positive sidebands. It is related to the net reflected electrical field corresponding to the thin film through :

$$\left.\begin{aligned}\mathrm{HCF}(\nu) &= \bar{\mathrm{r}}^{*}_{\mathrm{film}}(\nu).\mathrm{e}^{-\mathrm{i}4\pi\nu\overline{\Delta \mathrm{z}}_{\mathrm{HCF}}}\\ \bar{\mathrm{r}}_{\mathrm{film}}(\nu) &= \mathrm{HCF}^{*}(\nu).\mathrm{e}^{-\mathrm{i}4\pi\nu\overline{\Delta \mathrm{z}}_{\mathrm{HCF}}}\end{aligned}\right\}\text{..................}(2)$$

The HCF function therefore has the amplitude and phase *identical* to that of the conjugate of the net reflected electrical field apart from the exponent with the linear phase term (arising from the height difference between the measured coated and 'reference' substrate). Evidently, an exponent with such a linear phase term generates a helix.

The HCF function may therefore be determined over a range of frequencies within the two original Fourier positive sidebands. If the nominal structure of the thin film (multi)layer is known, then using the angular plane-wave spectrum approach together with standard matrix-based thin film analysis [2], the net theoretical electrical field reflectance and therefore the HCF function may be evaluated over the same range of frequencies. This allows the generation of a merit function (based on the quadrature sum of the real and imaginary differences between the extracted and fitted HCF functions) so that, using optimization, the thin film structure may be determined. In this instance, the conjugate gradient approach has been used [3].

RESULTS

The bulk of the experimental work has been carried out using a CCI 6000 Ultra Low Noise instrument [4,5]. In this paper, the approach taken is to concentrate on one particular sample prior to discussing other results obtained in the same manner.

Thin film key test sample

The key sample consists of a BK7 glass substrate (25mm diameter, 5mm thick) one side of which is partially coated with a symmetrical 3-layer structure, nominally 0.5H : L : 0.5H where H and L quarter-waves respectively of TiO_2 and SiO_2 at a nominal wavelength of 0.55µm. Having the substrate partially coated is advantageous since (i) a single measurement provides both the thin film and the BK7 reference measurements and (ii) it allows for independent measurement of the thin film structure by a contact stylus. In fact half of the partially coated face was over-coated with Cr to produce a final surface in the form of a set of quadrants, (i) uncoated BK7, (ii) triplet-thin-film coated BK7, (iii) Cr on BK7 and (iv) Cr on coated BK7. In addition to capturing the interference signals (fig. 1) for analysis, for subsequent verification purposes, the measured step-height for the 'raw' triplet edge and the Cr-coated 'correct' equivalent edge were 230nm and 189nm respectively. Additionally, a set of 5 Nanostep^5 step-height measurements gave the value 183.1± 8.8nm (2σ).

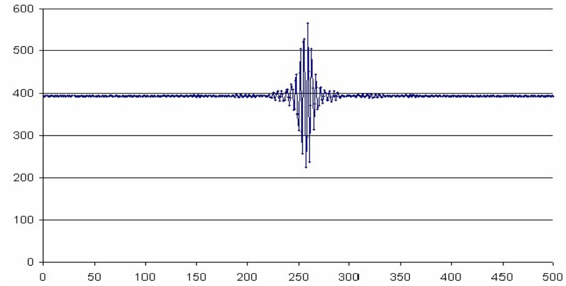

*FIGURE 1 : Interference signal corresponding to the mean of 16 locations for the triplet thin-film coating. The interference objective was a x10 Mirau (0.3NA) and the pixel-binning was 2*2. The surface area of the 16 locations was (10µm)^2*

HCF extraction and fitting

Together with the equivalent SWLI measurement of the 'reference' BK7 substrate, the application of eq. (1) directly generates the HCF function corresponding to the measured triplet thin film. Given that the form of this function is that of a scaled ratio of Fourier positive-arm sidebands, there is an inevitable degradation in signal/noise as the boundaries of the two component sidebands are approached (fig. 2). Through eq. (2) and the optimization approach described, the knowledge of the nominal thin film design then enables the experimentally derived real and imaginary components of the HCF function to be matched to an equivalent synthetic pair. In this instance, the optimised parameters for the triplet and Δz_{HCF} were : 0.573H : 0.970L : 0.573H and -69.2nm where H and L are quarter-waves of

TiO_2 and SiO_2 at 550nm. The very slight departures between the extracted and fitted components of the HCF function in fig. 2 are understood to be due to using Sellmeyer representations of the component dispersive refractive indices that are not perfectly mimicking the actual values; TiO_2 in particular is known to exhibit a dispersive index that clearly is a function of the particular thin-film deposition conditions.

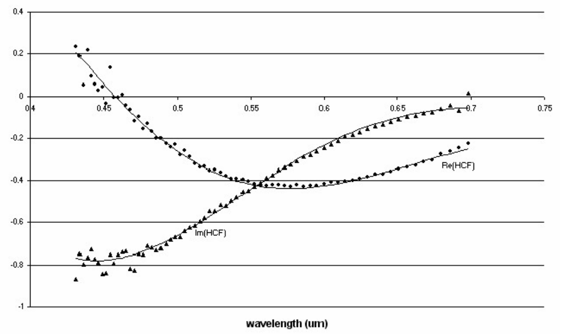

FIGURE 2 : HCF (Helical Conjugate Field) function corresponding to the triplet thin film sample. The real and imaginary components are shown. The solid lines are the corresponding real and imaginary components obtained through thin-film optimisation.

Electrical field reflectance

Having established the HCF function together with the value for Δz_{HCF}, it is then straightforward to apply eq. (2) to extract the electrical field reflectance. This is shown in fig 3.

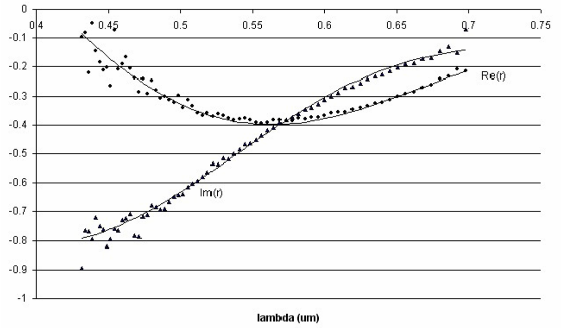

FIGURE 3 : Electrical Field reflectance for the triplet thin-film coating in terms of real and imaginary components. Also shown in solid lines are the corresponding components derived from the thin-film optimisation.

Phase-change on reflection (PCOR)

Having established the electrical field reflectance it is then trivial to re-express this in terms of PCOR. This is shown in fig. 4

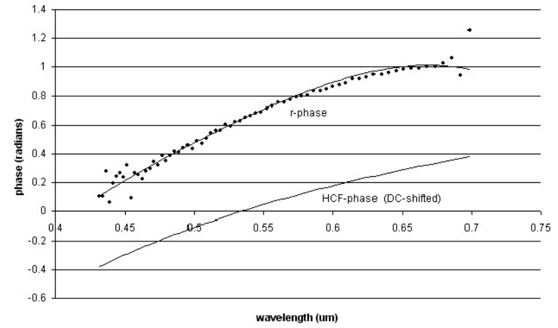

FIGURE 4 : PCOR for the triplet thin-film & (DC-shifted) HCF helical phase arising from ΔZ_{HCF}.

'Thin' thin-film measurement

The results of measuring and similarly characterising two further significantly thinner samples (A and B, respectively SiO_2 on Si and TiO_2 on BK7) are briefly presented in table 1.

	Sample A	Sample B
SWLI	3nm	82nm
PC-SWLI	35nm	79nm
Nanostep	28nm	74.9+-4.4nm
SWLI (Cr-coated)	----	75nm

Table 1 : Comparison of step-heights & film thicknesses

The corrected step-heights are clearly in broad agreement although less so than in the case of the triplet thin film. As the thin-film structure becomes progressively thinner, the phase term within the HCF function begins to be dominated by the layer dispersion and the amplitude of the HCF function becomes progressively featureless. In this regime, to maintain the level of uncertainty in the corrected step-heights, it becomes more important to characterise the dispersive index of the deposited thin film independently

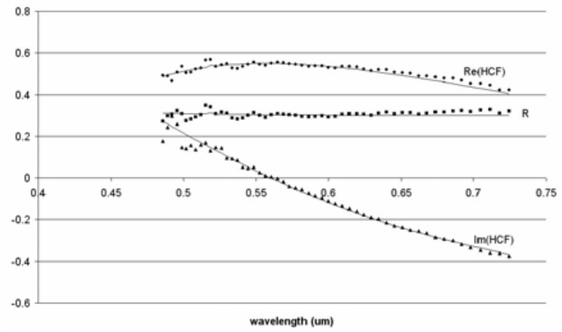

FIGURE 5 : Extracted and fitted HCF function (real and imaginary components) and spectral reflectance, R(v) (= $|HCF(v)|^2$) for sample A..

Single Location Performance

The results above have all been based on HCF functions generated from sets of 16 thin-film interference signals, each corresponding to 2*2 pixel-binning. It is useful to demonstrate the extent to which the signal/noise is compromised through using the thin film interference signal corresponding to a single location. As is apparent from fig. 6, the mid-band noise does exhibit the expected 1/N behaviour whereas at the short wavelength end in particular, this is not the case. Overall, the subsequent fitted parameters for the triplet and ΔZ_{HCF} were 0.564H : 0.974L : 0.564H and -69.6nm where H and L are quarter-waves of TiO_2 and SiO_2 at 550nm. This in turn yielded a corresponding PCOR-corrected step-height of 187nm, in very close agreement with the earlier result.

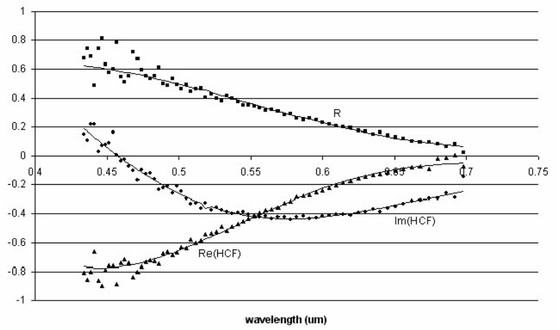

*FIGURE 6 : Extracted & fitted (solid lines) HCF functions (real & imaginary components) together with R, the reflectance corresponding to the triplet thin film sample. This data is derived from a single location interference signal set. the NA is 0.3 and the pixel-binning 2*2. The single location corresponds to an area of (2.5µm)^2.*

CONCLUSION

Scanning white light interferometry (SWLI) is now an established technique for the measurement of surface topography. It has the capability of combining sub-nanometre interferometric resolution with a range limited only by the z-traverse, typically at least 100µm. Through the introduction of the helical conjugate field (HCF) function, a useful additional capability has been demonstrated; this is the ability to measure thin films on a local scale - (2.5µm)^2 has been demonstrated. In addition to single layer thin films, layer thickness extraction for a 3-layered thin film has been demonstrated. Also, the related capabilities of step-height measurement through PCOR-correction and the measurement of the spectral reflectance on the same local scale have been demonstrated. In terms of the minimum film thickness limit of the approach, it has been shown that for single layer films of less than a quarter-wave in optical thickness, the amplitude of the HCF function becomes progressively featureless while the phase becomes dominated by the material dispersion; in this context it is best to have accurate independent knowledge of such dispersion.

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