Wide band interferometry for thickness measurement

Santiago Costantino and Oscar E. Martínez

Laboratorio de Electrónica Cuántica, Departamento de Física, Universidad de Buenos Aires, Pabellón 1, Ciudad Universitaria, C1428EHA Buenos Aires, Argentina
santiago@df.uba.ar

Jorge R. Torga

Laboratorio de Optica y Metrología Aplicada, Universidad Tecnológica Nacional, Regional Delta, San Martín 1171 (2804), Campana, Provincia de Buenos Aires, Argentina

Abstract: In this work we present the concept of wide band interferometry as opposed to white-light interferometry to introduce a thickness measurement method that gains precision when the bandwidth is reduced to an adequate compromise in order to avoid the distortions arising from the material dispersion. The use of the widest possible band is a well established dogma when the highest resolution is desired in distance measurements with white-light interferometry. We will show that the dogma falls when thickness measurements must be carried out due to material dispersion. In fact the precise knowledge of the frequency dependence of the refractive index is essential for adequate thickness retrieval from the optical experiments. The device we present is also useful to obtain the group refractive index that is necessary to calculate the absolute thickness value. As an example, we show the spreading of a silicone oil on a reference surface in real time.

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1. Introduction

The necessity of versatile methods to measure liquid and thin-film thickness is still unsatisfied. The highly accurate non-destructive optical method presented in this work overcomes many of the usual disadvantages of traditional methods and white-light interferometry, providing absolute thickness profiles with submicron resolution and high dynamic range.

Traditional interferometric profilometers and phase-shifting interferometers suffer from ambiguity problems in the phase-unwrapping process, so different algorithms have been created to provide an adequate solution [1, 2]. As a consequence, scanning white-light interferometry (SWLI) has been extensively used for unambiguous distance measurement with nanometer resolution along the propagation direction of a light beam. The use of a low coherence light source combined with the scanning of one arm of the interferometer provided a very useful way of measuring surface profiles [3-5]. Different techniques were developed to increase the system resolution over the coherence length of the source [6] and continuously provide diverse solutions to a variety of configurations [7, 8].

The need of mechanically stable environments and the necessity to perform a physical scan promoted the development of a method that combines low coherence sources together with spectral analysis of the interferograms. Instead of recording the intensity integrated in frequency for each Optical Path Difference (OPD), the intensity is measured for each wavelength and the distance is kept fixed [9, 10].

Some thin-film thickness measurement commercial devices use this principle; they use white-light as a source and perform a Fast Fourier Transform (FFT) algorithm to compute the thickness by calculating the modulation frequency. However, in order to get an accurate value for the thickness it is absolutely necessary to know the refractive index of the sample as a function of the wavelength for the whole detected spectrum, which is usually not taken into account. Besides, this is not an easy measurement to perform and the data is rarely available in the literature when the sample is not a commercial optical glass. Furthermore, if the material absorbs light within the source spectrum or the spectrum is not symmetric itself, different artifacts can corrupt the accuracy of the calculated thickness [11].

The measurement of liquid and thin-film thickness requires simple devices that can provide fast and accurate values in hostile environments, like the one we present in this work.

2. Wide band interferometry

In a Michelson or a Fizeau interferometer the intensity distribution can be described by

$$I(k,\ \Delta l) = I_{ref}(k) + I_{surf}(k) + 2\sqrt{I_{ref} I_{surf}} \cos(k\,\Delta l) \tag{1}$$

where I_{ref} and I_{surf} are the intensities from the reference and surface arms respectively, k is the wave vector and Δl is the OPD. If the interferogram is dispersed using a spectrometer, the intensity profile can be described by the spectrum of the light source modulated by a cosine function with a frequency that corresponds to the OPD. Consequently, a Fourier-transform analysis and the adequate filters enable to evaluate Δl without using any kind of phase unwrapping algorithms [9] and it becomes possible to measure the profile of a surface or the thickness of a thin-film by scanning the sample.

The dynamic range of this method is limited by the bandwidth of the light source for small OPDs and by the dispersion of the spectrometer and the detection system for large distances. In other words, for small distances the period of the modulation becomes comparable to the bandwidth of the light source and it is difficult to identify them in the Fourier space. On the other hand, when the OPDs are large, the modulation frequency of the spectrum becomes very high and the system resolution is limited by the dispersion of the spectrometer combined with the pixel size of the detection device.

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The precision of the system is related to the accuracy in computing a maximum in the Fourier plane. The number of pixels determine the frequency resolution of the Fourier transform, but the position of a peak center can be calculated with a much better precision in different ways, for example, fitting the function.

In order to calculate the thickness of a sample using optical methods it is necessary to know at least its refractive index. However, this magnitude is a function of the wavelength and it is possible to make a simple model to get a rough idea of how the dispersion of the refractive index modifies the modulation frequency of the interferogram spectrum [11]. We can estimate how the high order terms of this dispersion modify the modulation frequency as a function of the bandwidth of the light source.

Rewriting the interferometric term I_{int} in a complex form and a gaussian spectrum for the light source, with a bandwidth Δk, Eq. (1) becomes

$$I_{\text{int}}(k) = Exp\left(-\frac{[k-k_0]^2}{2\Delta k^2}\right) Exp\left(i\,k\,n(k)\,d\right) \tag{2}$$

Where c is the speed of light in vacuum, $n(k)$ is the refractive index, d is the thickness of the sample and k_0 is the central wave vector of the light source.

Considering the behavior of the refractive index as a function of k, it can be described by

$$n(k) = n_0 + \alpha(k-k_0) + \beta(k-k_0)^2 + \gamma(k-k_0)^3 + \ldots \tag{3}$$

where α, β and γ are the expansion coefficients. Combining Eq. (2) and Eq. (3) and expanding the refractive index up to first order in k it is possible to calculate the Fourier transform of the intensity analytically

$$I_{\text{int}}(x) \propto Exp\left(-\frac{\left[x-d\left(n_0+\alpha k_0\right)\right]^2 \Delta k^2}{2i+4\,d\,\alpha\,\Delta k^2}\right) \tag{4}$$

Where for simplicity we have neglected one term that has no information of the distance and normalization constants. The result shows that in the Fourier-transformed plane, there is a phase term and a gaussian centered at the thickness of the sample times the group index. When $n(k)$ is expanded up to higher orders there is no analytical solution and in order to evaluate how the dispersion affects the accuracy of the measurements we have numerically calculated the Fourier transform. For an optical glass sample it is possible to use the Sellmeier coefficients for different bandwidths and obtain the thickness.

Figure 1 shows the FFT of a wide band spectrum and Fig. 2 for white light using a 300µm SF56 sample. It is possible to see how the maxima of the functions get shifted due to the refractive index dispersion. The white light source that provides high precision in the case of nondispersive media, results in a loss of accuracy because of the broadening of the gaussian due to dispersion. Furthermore, considering second order dispersion results in another shift of the maximum and an asymmetry in the bell shaped curve in the Fourier space. In the case of wide band interferometry, none of these effects are noticeable.

In the case of nonsymmetrical spectrum of the light source and absorptive materials different effects appear that modify the shape of the transformed spectrum curve and require special attention in order to estimate the thickness.

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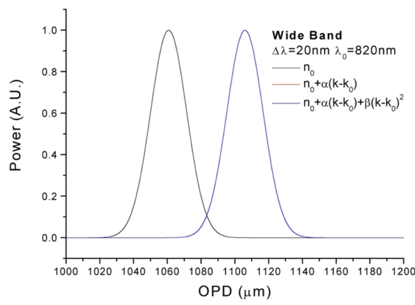

Fig. 1. FFT of a wide band spectrum for a 600µm SF56 sample. $\Delta\lambda$=20nm, λ_0=820nm

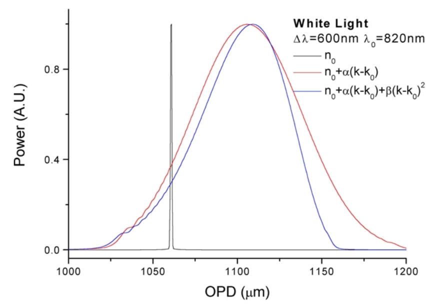

Fig. 2. FFT of a wide band spectrum for a 600µm SF56 sample. $\Delta\lambda$=600nm, λ_0=820nm

This result shows that in a noise free experiment a wide band light source should be used instead of white-light when the high order dispersion terms are large or unknown. The calculation of the relative error arising from not considering the dispersion of the refractive index for this sample yields 4.2% comparing zeroth and first order. Comparing first and second order dispersion, in the case of white light the relative error is $3x10^{-3}$ and in the case of wide band less than $1x10^{-5}$.

3. Experimental results

While in some situations a very wide spectrum is essential to measure the thickness of very thin films or liquids, the accuracy of the measurement does not improve using white light. Besides, the above mentioned relation between errors due to the high order dispersion terms make the wide band interferometer a very interesting device.

The experimental setup is shown in Fig. 3. The wide band light source consisted of a superluminescent diode laser centered at 820nm and with 20nm-bandwidth. The laser was focused on the sample and the beam reflected in the air-liquid interface interfered with the one coming from the reflective surface. After the beam splitter, the light is dispersed in a monochromator and the modulated spectrum of the light source is recorded using a 2048-pixels photodiode linear array connected to a computer performing an 8-bits A/D conversion at 200kHz. The spectrometer has a 1200g/mm grating and a focal length of 300mm. The dynamic range of this setup goes from a 20µm-thickness to 1mm approximately.

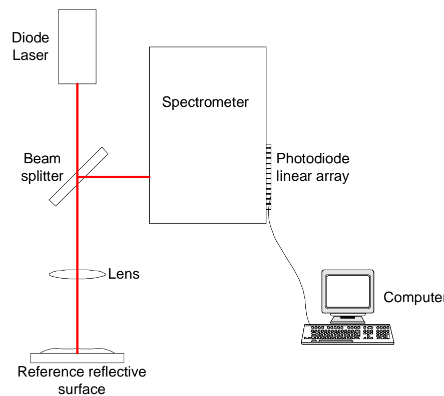

Fig. 3. Schematic of the Wide Band thickness measurement device.

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In order to test the device we have measured the thickness of a silicone oil drop (Sigma-Aldrich 14,615-3) spreading on the surface of a mirror in real time. To calculate the absolute thickness it was necessary to measure the effective refractive index, which can easily be done using the same device. Two sapphire windows were separated using a cover glass and placed in the interferometer in place of the sample. The air gap between them was measured using the wide band interferometer, the empty space was filled in with the sample oil and the frequency modulation was measured again. The ratio between these two OPDs provide a very good approximation for the group index as it was shown for the case of SF56.

$$\frac{x_m^{oil}}{x_m^{air}} \cong n_0 + \alpha k = n_0 - \lambda \frac{dn}{d\lambda} = n_g \qquad (5)$$

where λ is the wavelength, yielding n_g=1.440±0.001. The error of this magnitude is obtained using the standard deviation of each of the distance measurements which arises from the noise in the photodiode array.

A typical temporal profile of the thickness of a silicone oil drop while it spreads on the mirror surface can be observed in Fig. 4.

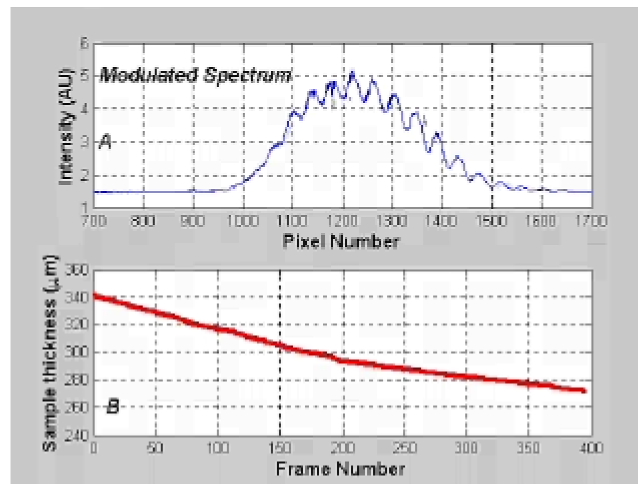

Fig. 4. (2.3MB) Movie showing the evolution of the thickness of a silicone oil drop on the surface of a metallic mirror as a function of time. A) Example of the laser diode spectrum modulated. B) Temporal evolution of the oil thickness.

In order to make a comparison between the wide band interferometer and a standard method it is possible to count the interference fringes while the oil layer gets thinner at the laser spot. As the thickness of the sample is larger than the coherence length of the light source, we have monitored the evolution of the phase for a particular wavelength λ_0 measuring the voltage of the central pixel.

Comparing the number of fringes and the distance obtained with the Fourier method using the calibration of the spectrometer at the time of the interference maxima, it is possible to fit a linear function. The slope s provides an expression to calculate the refractive index and its first order dispersion.

$$s = 1 - \frac{\lambda}{n_0} \frac{dn}{d\lambda} \qquad (6)$$

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Both magnitudes are plotted in Fig. 5 and a linear fit is done.

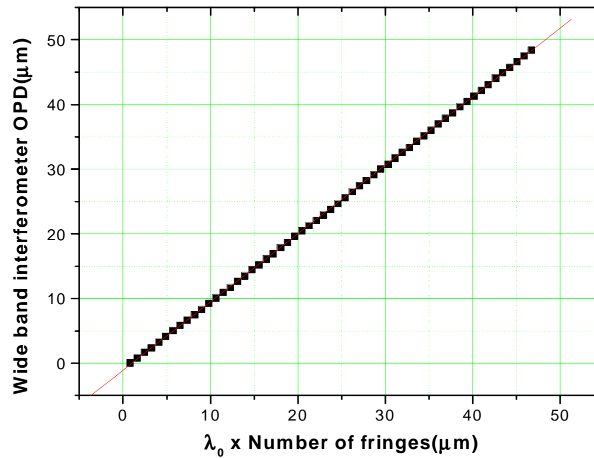

Fig. 5: Lubricant thickness change calculated using the calibration of the spectrometer as a function of the number of fringes times the laser wavelength. The slope of the linear fit has information to compute the first order dispersion of the refractive index.

Using Eq. (5) and Eq. (6) we computed the values for n_0=1.40±0.01 and $dn/d\lambda$=-0.0497±0.0005μm^{-1}, where the values of the errors are determined by the standard deviation of the linear fit performed in Fig. 5. In this situation the main contribution to the deviation value arises from the error in the determination of the interference fringes maxima.

4. Conclusions

We have presented in this paper a new technique to measure thickness in semitransparent media introducing the concept of wide band interferometry. We have also shown the advantages of using this method instead of classical white-light methods by calculating how the high order dispersion of the refractive index corrupts the accuracy of a thickness measurement and how this error can be reduced using this novel device.

We showed that this simple setup and a fast computing algorithm yields a thickness measurement with an statistical relative error of 10^{-3}. The magnitude of the error is originated in the low quality photodiode array that was employed. The accuracy obtained is in the order of the theoretical limits imposed by the index dispersion for low dispersive optical glass for white-light interferometry. Furthermore, the precision obtained using this method represents 300 times smaller than the coherence length of the light source. In other words, the coherence length is 30μm while, the absolute error of the measurements is 100nm and it is computed from the statistical distribution of the modulation frequency and it does not scale with the thickness of the sample.

We have also shown that the same setup can be used to obtain the group index and the first order index dispersion separately. As an example we have introduced a potential application of the device for liquid thickness determination with the additional advantage of real-time measurements.

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