A new interferometric method for the complete determination of the properties of the light field scattered from a rough surface

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ABSTRACT

Total Integrated Scattering (TIS) and Bi-directional Reflectance Distribution Function (BRDF) measurements give information on the mean roughness of the surface and on the modulus of the Fourier Transform of the 2D surface profile. To obtain a more precise description of a rough surface and to get an estimation of the relative contribution of surface and volume scattering in multilayers stack, we have developed a new interferometric method which allows us to measure the variation of the phase of the Fourier Transform of the surface profile as a function of the scattering angle. This paper includes a detailed presentation of this method, a description of the experimental set-up used for its principle validation, as well as some preliminary results that we have obtained with it on high reflectance samples.

Keywords : scattering, interferometry, phase, roughness

1. INTRODUCTION

In a general way, the roughness of an interface between two optical mediums can be described by a surface profile function h(x,y), which allows to quantify the height of the surface at a given point (x,y) with respect to a mean plane. If the height irregularities of this interface are much less than the wavelength of illumination :

$$\left| h(x,y)/\lambda \right| << 1$$

first order theories can be used to obtain BRDF and TIS values used for the description of the light scattering phenomena produced by such a surface [1, 2]. The BRDF is proportional to the square modulus of the 2D Fourier Transform of this surface profile function :

$$BRDF(\theta,\phi) \propto \left| \tilde{h}(\vec{\sigma}) \right|^2 ,$$

where $\vec{\sigma}$ is a spatial frequency vector defined by

$$\vec{\sigma} = \begin{bmatrix} \sigma_x \\ \sigma_y \end{bmatrix} = \frac{2\pi}{\lambda} \sin\theta \begin{bmatrix} \cos\phi \\ \sin\phi \end{bmatrix} ,$$

and $\tilde{h}$ the 2D Fourier Transform of the surface profile function, i.e. :

$$\tilde{h}(\vec{\sigma}) = \frac{1}{4\pi^2} \iint_{\vec{r}} e^{-j\vec{\sigma}.\vec{r}}\, h(\vec{r})\, d\vec{r} = \left| \tilde{h}(\vec{\sigma}) \right| e^{j\phi_{\tilde{h}}(\vec{\sigma})} .$$

The TIS is obtained by integrating the scattering distribution on the whole angular range, and as a consequence it does not include any kind of information on the phase term $\phi_{\tilde{h}}(\vec{\sigma})$ which is needed to recover the surface profile function by using for instance an inverse Fourier Transform method.

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Consequently, our objectives are :

- first, to define an experimental set-up able to perform the measurement of the variations of the phase term as a function of the scattering angle,
- second, to use both data (BRDF function and phase data) to reconstruct the profile of the surface with a resolution defined by the illumination wavelength and the scanned angular range,
- and, at the end, to use this method to obtain more precise information on the relative contributions of surface and volume scattering into a multilayer stack.

This paper is essentially devoted to the first item of this program.

2. BASIC PRINCIPLE

Let us consider a rough surface illuminated by a plane wave characterized by a wave vector $\vec{k}_i$ under an incidence angle noted *i* (state of polarization S) :

$$\vec{k}_i = \begin{bmatrix} \vec{\sigma}_i \\ \alpha_i \end{bmatrix} \text{ where } \alpha_\mathrm{i} = \frac{2\pi}{\lambda}\cos i.$$

Assuming that the roughness of the surface is small enough to allow the use of a first order theory, the light field $E_{s,s}^{(d)}$ scattered at a given angle θ_1 in the same state of polarization (S) is given by :

$$E_{s,s}^{(d)}(\vec{k}_d) = -j\,\frac{2\pi}{\lambda}\,\frac{n_1^2 - n_0^2}{n_1\cos r + n_0\cos i}\cos(\phi_d - \phi_i)\,\tilde{h}(\vec{\sigma}_d - \vec{\sigma}_i)\,E_s^{(i)}(\vec{k}_i) = C\left|\tilde{h}(\vec{\sigma}_d - \vec{\sigma}_i)\right| e^{j\phi_{\tilde{h}(\vec{\sigma}_d - \vec{\sigma}_i)}}\,E_s^{(i)}(\vec{k}_i)$$

where C is an optical factor which depends only of the illumination and observation conditions (n_1 and n_0 are the refractive indices of the substrate and of the surrounding medium, while ϕ_d and ϕ_i are the polar angles respectively associated to the incident and scattered waves).

Recording only intensity variations of the scattered field with respect to the angle θ, as achieved by BRDF measurements, does not permit to recover the phase information. To measure the phase, **interference phenomena** either between the light beams scattered at two different angles or between the incident beam and a scattered one is needed. In this case, superposing the two beams and eliminating the effects of mechanical drifts is required.

Our method overcomes these difficulties (see Figure 1). We replace the interference between two light beams scattered at two different angles by the interference between the light beams scattered at the **same angle** by **two** coherent but **separate light beams**. The two beams illuminate the same area of the sample surface under two different incidence angles. This scheme has been described in other papers [3, 4] but, to our knowledge, it has never been used to measure the phase of the scattered field.

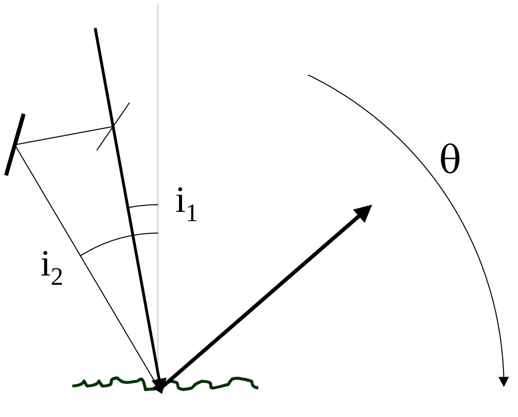

Figure 1

The condition of coherence required between the two incident beams can be easily fulfilled by sharing a single optical beam into two separate beams thanks to a beam splitter, as shown in Figure 1. Here the rough surface plays the role of the beam combiner of a classical two beams interferometer like a Mach-Zehnder.

The main advantage of this optical scheme is to be self aligned, the quality of the overlapping between the two incident beams having only impacts on the visibility of the interference phenomena. This attractive feature allows to envisage without too great difficulties the recording of the phase variations associated to a given part of a rough surface when the scattering angle is scanned between 0 and 90°.

The light intensity which results from the coherent mixing of the two incident beams (1 and 2) at the sample surface is done by

$$I = \left| E_{s,s}^{(d)}(1) + E_{s,s}^{(d)}(2) \right|^2 .$$

If we neglect the variation of the optical factor C with respect to the incident angle, and if we assume that the used configuration corresponds to an in plane one (polar angles equal to zero), we can write

$$I = |C|^2 \left\{ I_1 \left|\tilde{h}(1)\right|^2 + I_2 \left|\tilde{h}(2)\right|^2 + 2\sqrt{I_1 I_2}\ \left|\tilde{h}(1)\right| \cdot \left|\tilde{h}(2)\right| \cos\psi \right\} ,$$

where I_m is the intensity of the incident beam m, $\left|\tilde{h}(m)\right|^2$ the light scattering efficiency in the θ direction for the same m beam and ψ a phase shift defined by

$$\psi = \frac{2\pi\Delta}{\lambda} + \phi_{\tilde{h}}(\vec{\sigma}_d - \vec{\sigma}_{i2}) - \phi_{\tilde{h}}(\vec{\sigma}_d - \vec{\sigma}_{i1}),$$

where Δ is the optical path difference accumulated in the interferometer from the beam splitter to the sample surface (from the surface to the detector, the paths associated to the two beams are rigorously identical).

In order to allow an accurate measurement of the phase difference associated to the scattering phenomena, two main problems remain to solve :

- the first problem is due to the presence of the **Δ term** in the expression of the resulting phase information : it means that the mechanical drifts of the set-up can affect dramatically the result of our measurements ; this effect can be easily cancelled by adding to our set-up a reference channel corresponding to a fixed scattering angle θ_0 and by subtracting at each time the corresponding ψ_0 quantity to the previous one. As a consequence, our final measurement result R will be equal to

  $$R = \psi(\theta) - \psi(\theta_0) = \left[\phi_h(\vec{\sigma}_d - \vec{\sigma}_{i2}) - \phi_h(\vec{\sigma}_d - \vec{\sigma}_{i1})\right] - \left[\phi_h(\vec{\sigma}_0 - \vec{\sigma}_{i2}) - \phi_h(\vec{\sigma}_0 - \vec{\sigma}_{i1})\right]$$

- the last problem is connected with **speckle effect** and correlated averaging phenomena : the roughness of the surface induces the appearance of a high contrast intensity modulation into the scattered fields, and accordingly, a fast variation of the $\left|\tilde{h}(m)\right|^2$ terms with respect to the detection angle θ. If we use large area detectors to record the overall scattered intensity, we perform an averaging of the different terms on a given angular range[5,6] and the resulting apparent phase can be completely wrong because of combined effects of fast intensity variations and intrinsic non-linearity of the phase/intensity relation. To overcome any kind of parasitic averaging phenomena, we have chosen to reduce the optical throughput of the detection beam to λ^2, the optical throughput of a single optical mode, which is easily achieved with the use of singlemode fibers.

3. EXPERIMENTAL SET-UP

The experimental set-up that we have developed to validate the principle of our method is schematized in the Figure 2.

The light beam provided by a He-Ne laser (632.8 nm ; 7 mW) is polarized (polarization ratio better than 1000:1), then divided into two separate beams with the help of a beam splitter. The beam reflected by this beam splitter is reflected by a plane mirror and illuminates the sample under an incidence angle of about 10°. The beam transmitted by the same beam splitter propagates through an electro-optic phase modulator (EOPM) and an adjustable Optical Path Delay (OPD) and up to the same sample (incidence angle approximately equal to zero). The overlapping of the two beams at the sample surface can be optimized with a fine adjustment of the orientation of the plane mirror.

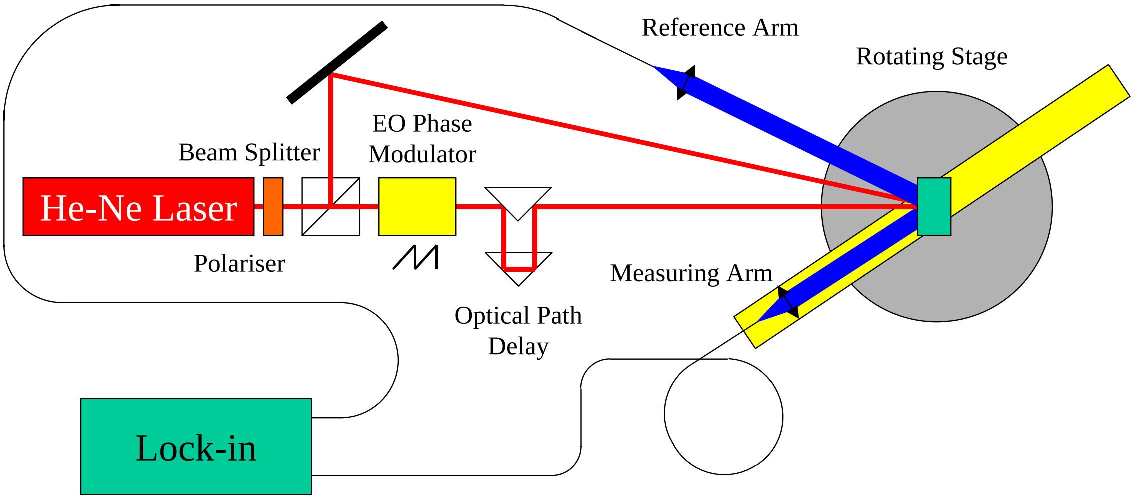

Figure 2

The use of an adjustable OPD assembly allows us to equalize approximately the optical path of the two arms of this interferometer, which avoids a possible decrease of the visibility of the interference phenomena induced by the relatively small coherence length of the source (about 10 cm).

The measuring arm includes a single mode fiber whose one of the extremities is located in the focal plane of a single aspheric lens, while the other is directly connected to a Silicon photodiode used into the photovoltaïc mode. High performances current/voltage transformers are used to amplify the electrical current provided by the photodiode to a sufficient level. The angular position of this measuring arm can be scanned between 10° and 90° with the help of a motorized rotating stage.

The reference arm is identical to the measuring arm, but it is mounted at a fixed angular position with respect to the sample (about –20°).

By applying on the EOPM device (Niobate Lithium crystal) a saw-tooth voltage modulation whose amplitude corresponds to a 2π phase shift, we induce a linear phase modulation of the signal, which allows to implement a synthetic heterodyne detection scheme to recover the phase information : the phase of the optical signal is also transferred into the phase of a pure sine electrical signal whose frequency is equal to that of the saw-tooth signal.

By using a lock-in amplifier in its phase detection mode, we obtain directly the R phase term introduced at the section 2.

4. PRELIMINARY RESULTS

The experimental set-up described at the previous section is able to record :

- the speckle field associated to the incoherent superposition of the two illuminating beams (DC term provided by the photodiode), as well as the elementary speckle fields corresponding to each beam (stop installed on the other),
- the intensity of the coherent mixing of these two speckle fields (AC term recorded at the frequency of the phase modulation and available at the amplitude output of the lock-in amplifier),
- the resulting phase difference R (phase output of the same lock-in amplifier).

Taking into account some detectivity limitations of our set-up (the light levels collected into single mode fibers are naturally low), we have chosen to start our experimental studies by using high reflectance samples (scattering standard).

Figure 3 shows the profile of the speckle fields recorded in a single beam configuration on a 4° range, between 11.5° and 15.5°. By using the theoretical relation established at the section 2, we can compute the expected intensity of their coherent mixing and compare this result with the direct measurement performed through the lock-in amplifier. This comparison is a very good test of the lack of averaging into our measurement process.

The result of this comparison is provided on the same 4° range as before at the Figure 4, and the agreement between the two profiles is very satisfying, even if a small averaging phenomena can be detected on a small interval of about 0.05°.

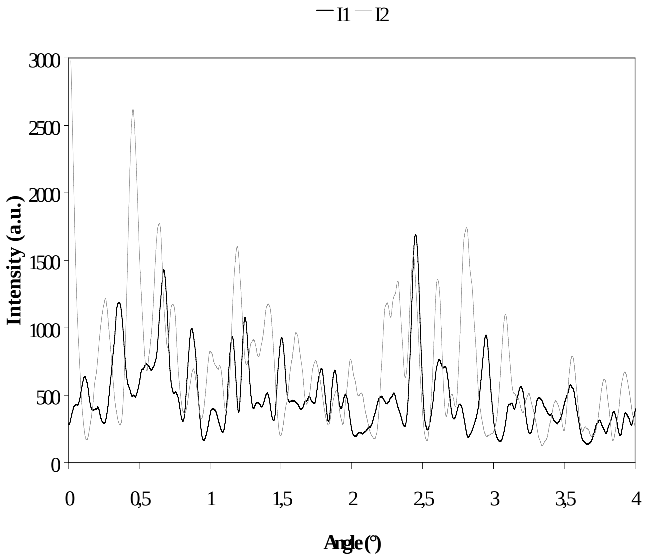

Figure 3

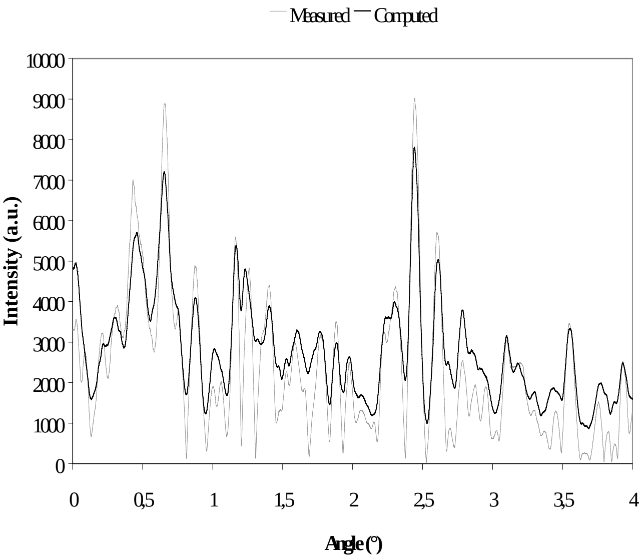

Figure 4

We shall notice that the quality of this agreement is the same in the whole measuring range.

Figure 5 shows the shape of a phase profile recorded on a 16° angular range between 7.5° and 23.5°, while Figure 6 provides with a zoom of the previous graph on a 2° range starting at 7.5°. The phase information presents naturally a 2π indetermination, which explains the vertical transitions that appear for some positions. The reproducibility of these measurements is very high (no detectable difference between two files recorded in the same conditions).

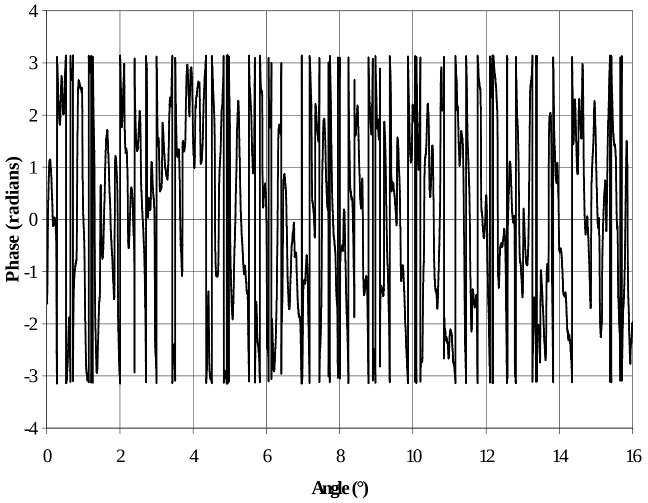

Figure 5

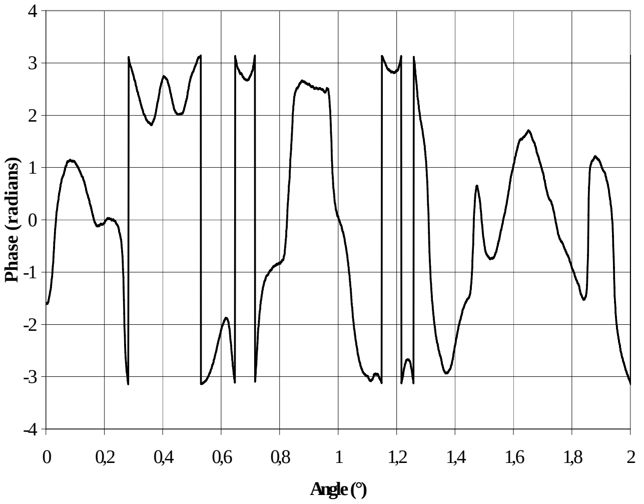

Figure 6

The last verification that we have made at the present time with this set-up is to study the influence of a small displacement (up to 100 μm) of the sample in its plane, the diameter of the illuminated area being about 1 mm. In this case, the surface profile function shall be slightly modified by such a displacement and we can expect that the changes of the phase files recorded at low scattering angles remain small.

Curves of Figures 7 and 8 obtained for a 4° variation between 7.5° and 11.5° of the scattering angle (in-plane displacement respectively equal to 20 and 80 µm) have confirmed the theoretical predictions.

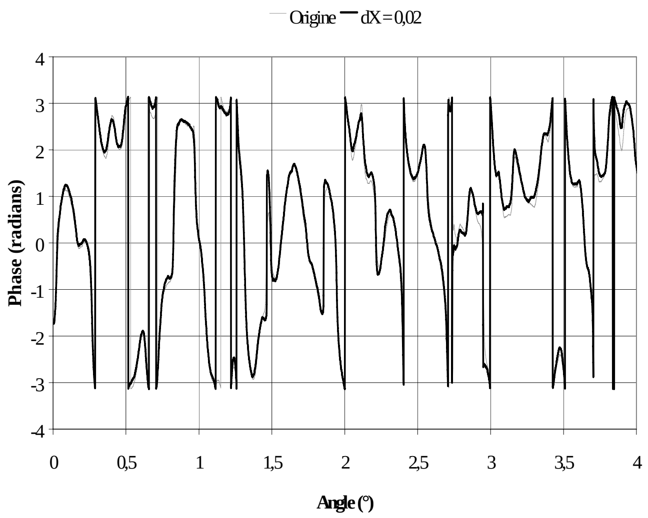

Figure 7

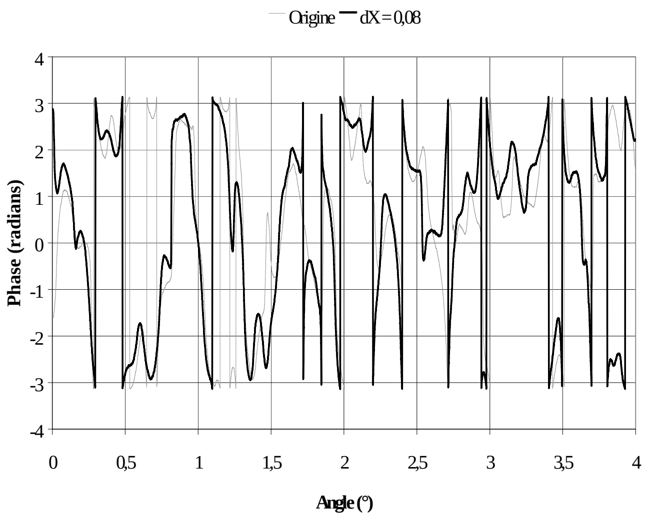

Figure 8

5. CONCLUSIONS

The feasibility of this new optical characterization method is now well established and practical methods to cancel the influence of some parasitic effects (mechanical drifts, speckle averaging) have been proposed and experimentally verified.

Some improvements are still required to allow its practical use on low roughness samples, because of the poor optical efficiency of the measurement channels (very low optical throughput). These improvements include an increase of the light power available at the surface sample and an increase of the sensitivity of the detection means.

This method can be an alternative and complementary tool to classical scattering measurements (TIS and BRDF), to ellipsometric measurements performed on the diffuse part of the BRDF[7] or to direct surface measurements (Atomic Force Microscope, White Light Interferometry).

6. REFERENCES

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