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Application of Young Slits Technique: Measurement of the Phase of the Diffracted Field in Optical Domain

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Abstract: This study presents a new technique to measure the phase difference between two diffracted fields: The field diffracted by a reference object and the field diffracted by an unknown object. For that we use the interferential technique of Young slits. We measured the phase difference between the diffracted fields of two rods of resin. And knowing the phase of the diffracted field of the reference object helps deducing the phase of the field diffracted by the sample. This setup is simple and it is very strong in the presence of disturbances because both objects are illuminated with the same incident beam. Moreover, this technique allows us measuring the phase of the diffracted field on a wide range of angle so that a high resolution of the image can be obtained.

Key words: Phase difference, optical diffraction tomography, optical microscope, diffracted field

INTRODUCTION

There has been a considerable interest these last few years in the development of new optical imaging systems that are able to give the three dimensional optical properties of a sample, as encoded in the spatial variations of the permittivity, at the nanoscale (Carney *et al*., 2004; Sentenac *et al*., 2006; Liu *et al*., 2007). Potential applications range across multiple fields in life and material sciences.

Standard optical microscopes do not provide quantitative information on the sample permittivity. Crucial information is lost when only the intensity of the diffracted field is detected. To overcome this difficulty, it has been proposed to measure the amplitude and the phase of the diffracted field in a conventional far field microscope and to increase the resolution of the imager, the sample is illuminated under various incident angles (Lauer, 2002). An inversion algorithm is then used to form the image from the multiple dataset (Belkebir and Sentenac, 2003). This approach, known as Optical Diffraction Tomography (ODT) has stirred a wealth of research in the last five years and different setups, adapted to biological applications (Lauer, 2002; Debailleul *et al*., 2008) or to surface imaging (Alexandrov *et al*., 2006; Mico *et al*., 2006) were proposed.

Herein, we present a setup which allowed us to measure the phase of the diffracted field on a wide range of angle. So far, in the experimental configuration used to measure the phase of the diffracted field, the underlying principle is interference between a probe beam and a reference beam (Lauer, 2002; Destouches *et al*., 2001). We use here only one beam in this set up.

SETUP

The interferential technique of Young slits is composed of two slits in the same plane. These two slits are lit by the same incident beam. The waves diffracted by these two slits interfere to give the

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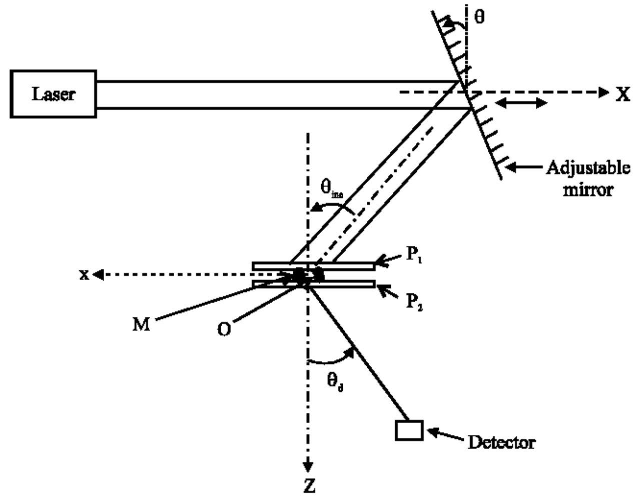

Fig. 1: Setup diagram, O is the sample deposited on the fine glass plate P_1 and M is the reference object deposited on the fine glass plate P_2

interference figure of young slits. In the far field, there is an interference between the fields diffracted in the same direction. The angle of observation, θ_d, defined as the angle between the diffracted wave vector $\vec{k}_d$ and the z-axis, can range from $-80°$ to $80°$.

For the other interferential systems, i.e., the Michelson interferometer, the angle of observation ranges from $-45°$ to $45°$ at the best, when using a cube as a beam splitter.

There are two things to consider in this setup: the reference object and the sample. Let us denote $\phi_{ref}(\vec{k}_{inc}, \vec{k}_d)$ the phase of the field scattered by the reference object, where, $\vec{k}_{inc}$ is the wave vector of the incident wave and $\vec{k}_d$ the wave vector of the diffracted wave. Figure 1 shows the diagram of the setup.

The reference object and the sample we use in this experiment are rods of resin, with rectangular cross-sections, deposited on a glass substrate. The relative permittivity of this resin is $\varepsilon_r = 2.66$. The incident plan and the polarization of the illuminating wave are perpendicular and parallel to the invariant axis of the rods, respectively.

The emitted light at 633 nm by a 30 mW Helium-Neon laser, illuminates the reference object and the sample. The reference object is translated along the x-axis direction by an electro optic modulator, so that the reference object does not leave the illuminated beam. With a photodetector placed on a moving arm which turns around the sample, the intensity I_{rd} of the interference between the diffracted field of the sample and the diffracted field of the reference object is measured for different angles. The moving arm is 60 cm long so that we work in the far field region.

We assume that the illuminated wave $\vec{E}_{inc}$ is a plane wave and that the diffracted waves do not illuminate any object.

$$\vec{E}_{inc} = A_i \exp(j\Delta\phi) \tag{1}$$

where, A_i and $\Delta\phi$ are, respectively the amplitude and the phase of the illuminating field.

The diffracted field of the sample is:

$$\vec{E}_d(\vec{k}_{inc}, \vec{k}_d) = A_d(\vec{k}_{inc}, \vec{k}_d) \exp j\left[\Delta\phi + \phi_d(\vec{k}_{inc}, \vec{k}_d)\right] \tag{2}$$

where, $A_d(\vec{k}_{inc}, \vec{k}_d)$ and $\phi_d(\vec{k}_{inc}, \vec{k}_d)$ are, respectively the amplitude and the phase of the field. The diffracted field of the reference object is:

$$\vec{E}_{ref}(\vec{k}_{inc},\vec{k}_d) = A_{ref}(\vec{k}_{inc},\vec{k}_d)\exp j\left[\Delta\phi + \phi_{ref}(\vec{k}_{inc},\vec{k}_d) + (\vec{k}_{inc} - \vec{k}_d).\overrightarrow{OM}\right] \tag{3}$$

where, $A_{ref}(\vec{k}_{inc},\vec{k}_d)$ and $\phi_{ref}(\vec{k}_{inc},\vec{k}_d)$ are, respectively the amplitude and the phase of the field diffracted by the reference object in the direction of $\vec{k}_d$.

Assuming that $\overrightarrow{OM} = d\vec{u}_x$ then:

$$\begin{aligned} I_{rd}(\vec{k}_{inc},\vec{k}_d) &= I_{ref}(\vec{k}_{inc},\vec{k}_d) + I_d(\vec{k}_{inc},\vec{k}_d) + 2\left[I_{ref}(\vec{k}_{inc},\vec{k}_d).I_d(\vec{k}_{inc},\vec{k}_d)\right]^{1/2} \\ &\quad {}^*\cos\left[\phi_d(\vec{k}_{inc},\vec{k}_d) - \phi_{ref}(\vec{k}_{inc},\vec{k}_d) + (\vec{k}_d - \vec{k}_{inc}).d\vec{u}_x\right] \end{aligned} \tag{4}$$

where, $I_{ref}(\vec{k}_{inc},\vec{k}_d)$ and $I_d(\vec{k}_{inc},\vec{k}_d)$ are the intensities of the scattered field of the reference object and the sample respectively in the direction of $\vec{k}_d$ and $I_{rd}(\vec{k}_{inc},\vec{k}_d)$ is the intensity of the interference between the diffracted field of the sample and the diffracted field of the reference object in the direction of $\vec{k}_d$.

$$\begin{aligned} I_{rd}(\vec{k}_{inc},\vec{k}_d) &= I_{ref}(\vec{k}_{inc},\vec{k}_d) + I_d(\vec{k}_{inc},\vec{k}_d) + 2\left[I_{ref}(\vec{k}_{inc},\vec{k}_d).I_d(\vec{k}_{inc},\vec{k}_d)\right]^{1/2} \\ &\quad {}^*\cos\left[\phi_d(\vec{k}_{inc},\vec{k}_d) - \phi_{ref}(\vec{k}_{inc},\vec{k}_d) + \frac{2\pi}{\lambda}d(\sin\theta_d - \sin\theta_{inc})\right] \end{aligned} \tag{5}$$

We assume that the translation is proportional to the tension: $d = kV$ so,

$$\begin{aligned} I_{rd}(\vec{k}_{inc},\vec{k}_d) &= I_{ref}(\vec{k}_{inc},\vec{k}_d) + I_d(\vec{k}_{inc},\vec{k}_d) + 2\left[I_{ref}(\vec{k}_{inc},\vec{k}_d).I_d(\vec{k}_{inc},\vec{k}_d)\right]^{1/2} \\ &\quad {}^*\cos\left[\phi_d(\vec{k}_{inc},\vec{k}_d) - \phi_{ref}(\vec{k}_{inc},\vec{k}_d) + \frac{2\pi}{\lambda}kV(\sin\theta_d - \sin\theta_{inc})\right] \end{aligned} \tag{6}$$

The signal s (θ_d, θ_{inc}) is evaluated:

$$s(\theta_d,\theta_{inc}) = \frac{I_{rd}(\vec{k}_{inc},\vec{k}_d) - I_{ref}(\vec{k}_{inc},\vec{k}_d) - I_d(\vec{k}_{inc},\vec{k}_d)}{2\left[I_{ref}(\vec{k}_{inc},\vec{k}_d).I_d(\vec{k}_{inc},\vec{k}_d)\right]^{1/2}} \tag{7}$$

$$s(\theta_d,\theta_{inc}) = \cos\left[\phi_d(\vec{k}_{inc},\vec{k}_d) - \phi_{ref}(\vec{k}_{inc},\vec{k}_d) + \frac{2\pi}{\lambda}kV(\sin\theta_d - \sin\theta_{inc})\right] \tag{8}$$

We determine k and then we calculate the signal:

$$s_{cal}(\theta_d,\theta_{inc}) = \cos\left[\frac{2\pi}{\lambda}kV(\sin\theta_d - \sin\theta_{inc})\right] \tag{9}$$

With both signals s (θ_d, θ_{inc}) and s_{cal} (θ_d, θ_{inc}), we estimate $\phi_d(\vec{k}_{inc},\vec{k}_d) - \phi_{ref}(\vec{k}_{inc},\vec{k}_d)$ for various observation directions $\vec{k}_d$.

RESULTS AND DISCUSSION

$\phi_d(\vec{k}_{inc},\vec{k}_d) - \phi_{ref}(\vec{k}_{inc},\vec{k}_d)$ is determined when the reference object and the sample are illuminated using a beam in the normal direction $\theta_{inc} = 0$. The results are shown in Fig. 2-5.

Figure 6 and 7 show the results when the reference object and the sample are illuminated by the incident beam with the angle of incident $\theta_{inc} = 37°$.

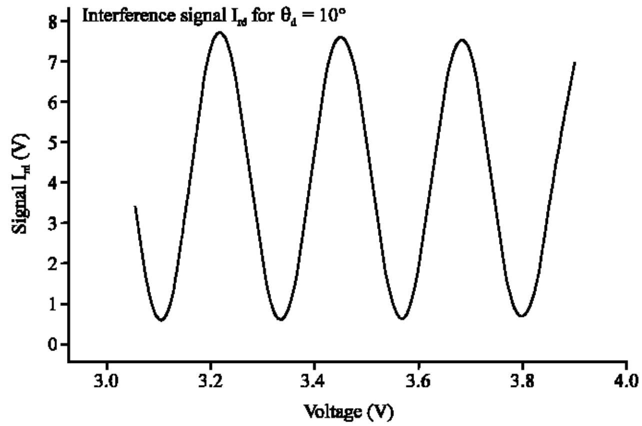

Fig. 2: Intensity of the interference between the diffracted field of the sample and the diffracted field of the reference object for $\theta_{inc} = 0$ and $\theta_d = 10°$

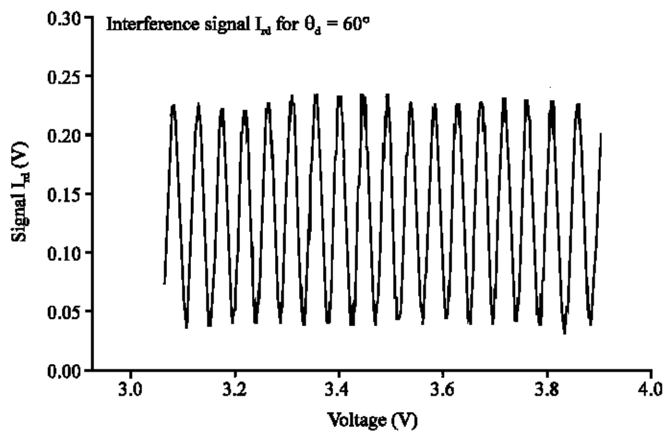

Fig. 3: Intensity of the interference between the diffracted field of the sample and the diffracted field of the reference object for $\theta_{inc} = 0$ and $\theta_d = 60°$

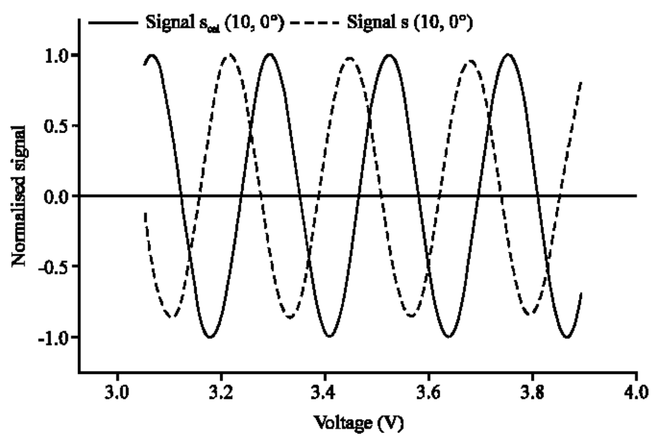

Fig. 4: Experimental signal s (θ_d, θ_{inc}) and calculated signal s_{cal} (θ_d, θ_{inc}) for $\theta_d = 10°$ and $\theta_{inc} = 0°$

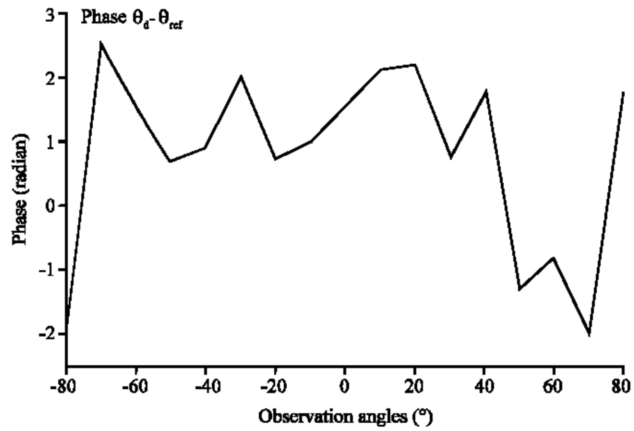

Fig. 5: Experimental signal $\phi_d(\vec{k}_{inc},\vec{k}_d)-\phi_{ref}(\vec{k}_{inc},\vec{k}_d)$ for $\theta_{inc} = 0°$

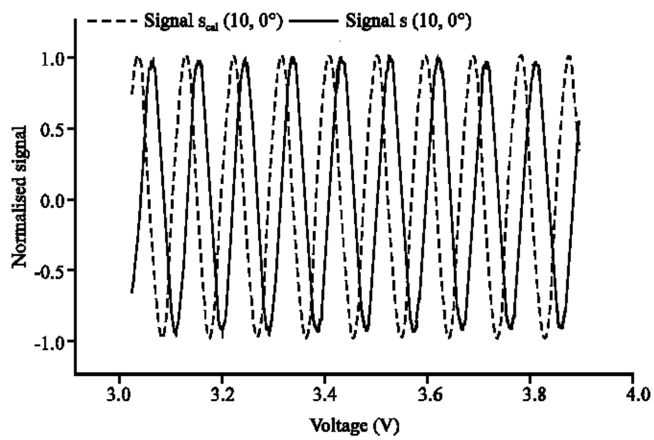

Fig. 6: Experimental signal s (θ_d, θ_{inc}) and calculated signal s_{cal} (θ_d, θ_{inc}) for $\theta_d = 10°$ and $\theta_{inc} = 37°$

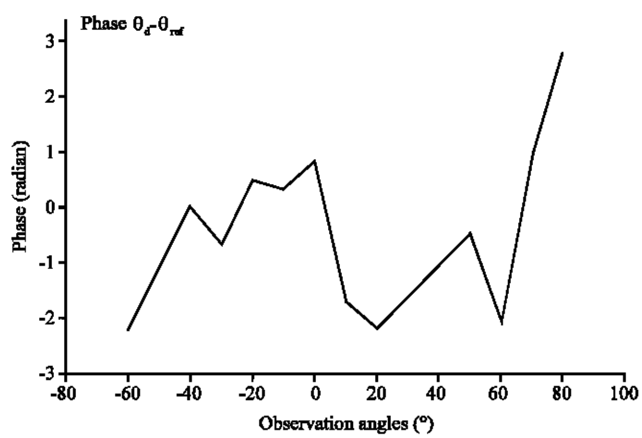

Fig. 7: Experimental signal $\phi_d(\vec{k}_{inc},\vec{k}_d)-\phi_{ref}(\vec{k}_{inc},\vec{k}_d)$ for $\theta_{inc} = 37°$

When we compare the measured signal with the calculated signal (Eq. 9) with the good phase shift for this direction, we note a very good agreement between the two signals.

The intensity of the interference between the diffracted field of the sample and the diffracted field of the reference object for $\theta_d = 60°$ is not very noisy. This allows measurements on a wide range of angle for a given direction of incidence.

Comparing with the other tomography techniques, this technique presents two main advantages. Firstly it uses only one beam, not two and secondly it allows measures on a wide range of angle for a given direction of incidence.

A number of directions of the illuminating wave are used and the corresponding intensities of the interferences are measured. Following this, the corresponding phases $\phi_d(\vec{k}_{inc},\vec{k}_d) - \phi_{ref}(\vec{k}_{inc},\vec{k}_d)$ are determined. And knowing $\phi_{ref}(\vec{k}_{inc},\vec{k}_d)$, we deduce the phase of the diffracted field of the sample $\phi_d(\vec{k}_{inc},\vec{k}_d)$.

CONCLUSION

A simple setup based on Young slits technique has been built. It has allowed making measurements of difference phase of the diffracted fields without using lenses. These measurements have been made on a wide rang of angle [−80°, 80°]. That helps to have a high resolution of the imager. Moreover, this setup is very strong in presence of disturbances.

With the different results, it is experimentally demonstrated that it is possible to measure the phase of the diffracted field. A further study is projected in order to improve this technique by motoring the movement of the detector.

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