Interferometric configuration based on a grating interferometer for the measurement of the phase between TE and TM polarizations after diffraction by gratings

H. Giovannini and H. Akhouayri

Laboratoire d'Optique des Surfaces et des Couches Minces, U.R.A. 1120, Centre National de la Recherche Scientifique, Ecole Nationale Supérieure de Physique de Marseille, 13397 Marseille Cedex 20, France

Received June 26, 1995

Ellipsometers permit the measurement of the phase between s and p polarizations with high accuracy. However, for some applications such high accuracy is not required. A configuration based on a grating interferometer is an attractive solution that permits, with the use of a polarizer and a ferroelectric liquid-crystal retarder, the measurement of the phase between s and p polarizations after diffraction by gratings. This device can find applications in the field of optical fiber sensors.

The theory of a field diffracted by gratings is now well known.[1–4] Many studies have been carried out to increase the efficiency of gratings for spectrometric measurements. However, for most applications only the intensity of the diffracted wave is measured, and the phase between the incident and the diffracted fields is not taken into account. Nevertheless, in order to solve the inverse problem[5] and to determine the physical parameters (spacing, shape, complex indices) of gratings, it may be useful to know the phase change after diffraction for TE and TM polarizations. This problem has been studied theoretically, and experimental devices based mostly on ellipsometric arrangements have permitted confirmation of the results obtained by numerical simulations. It has been shown that, for TM polarization and for metallic gratings, the phase change after diffraction varies rapidly near the plasmon resonances.[1,2,4] We describe a configuration based on a grating interferometer[6] that permits measurement of the phase change after diffraction between TE and TM polarizations. This configuration, which is easy to set up, makes it possible to perform the measurement without the sophisticated calibration process required in conventional ellipsometers. Moreover, so that critical adjustments can be avoided, the change of polarization state in one arm of the interferometer is obtained with no moving parts. The experimental results obtained with ruled metallic gratings are presented: the possibility of using this device as a receiver interferometer for a network of optical fiber sensors is demonstrated.

The grating interferometer shown in Fig. 1 is illuminated by a collimated beam with monochromatic radiation whose wavelength is λ_0. The two gratings, G_1 and G_2, are in Littrow mounts for wavelength λ_0. The grooves of G_1 and G_2 are parallel. In this case the wave fronts after diffraction by the gratings are parallel, and the grating interferometer is equivalent to a Michelson interferometer with a uniformly illuminated field of interferences. G_1 and G_2 are in Littrow mounts for the diffracted orders n and m, respectively, and these reflected orders interfere after passing through beam splitter BS. We can change n and m by rotating G_1 and G_2 around a vertical axis. The output light is then focused onto detector D. The ferroelectric liquid-crystal cell, C, is used to rotate the linear polarization given by polarizer P, which is parallel to the grooves of G_1 and G_2. For an applied voltage V_1, C is a half-wave birefringent plate whose ordinary axis is parallel to the input polarization. This implies that the two incident beams on the gratings are s polarized. The length of one arm of the interferometer is modulated by a voltage ramp applied to piezoelectric transducer, PZT. Assuming that the BS is a 50/50 beam splitter for TE polarization and that the interferometer is perfectly adjusted, the signal recorded at the output of D is

$$S_1 = (I_{\mathrm{TE1}}^n + I_{\mathrm{TE2}}^m)\left\{1 + \frac{\sqrt{I_{\mathrm{TE1}}^n I_{\mathrm{TE2}}^m}}{I_{\mathrm{TE1}}^n + I_{\mathrm{TE2}}^m}\cos[kL(t) + \phi_{\mathrm{TE}}^{nm}]\right\}, \tag{1}$$

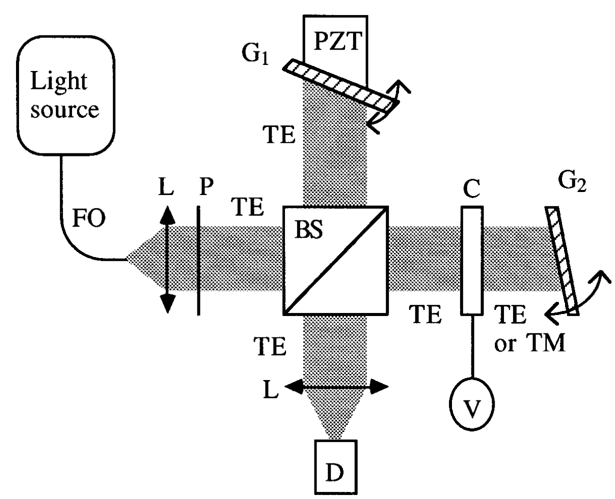

Fig. 1. Schematic of the grating interferometer. G_1 and G_2 are not necessarily identical, and they can be rotated to change the order of the Littrow mount. L's, lenses; FO, fiber optic.

0146-9592/95/212255-03$6.00/0

where I^n_{TE1} is the intensity of the light reflected by G_1 in Littrow order n, I^m_{TE2} is the intensity of the light reflected by G_2 in Littrow order m when G_1 and G_2 are both illuminated with TE polarization, $k = 2\pi/\lambda_0$, and

$$\phi^{nm}_{TE} = \phi^n_{TE1} - \phi^m_{TE2}, \tag{2}$$

with ϕ^n_{TE1} and ϕ^m_{TE2} the phase differences between the incident field and the field diffracted by G_1 in Littrow order n and by G_2 in Littrow order m, respectively, for TE polarization. To obtain Eq. (1) we have to neglect the reflection and the transmission losses. In Eq. (1) t is time and

$$L(t) = L_0 + l(t) \tag{3}$$

is the difference between the lengths of the two arms of the interferometer, with L_0 the value of L at $t = 0$. For an applied voltage V_2, the ordinary axis of C rotates by 45° with respect to the first state. In this case, G_1 is illuminated by a TE polarization, while G_2 sees an incident TM polarization. After the counterpropagating wave is reflected by G_2 and passes through C, its polarization changes to TE. The two diffracted waves interfere, and the signal recorded at the output of D is

$$S_2 = (I^n_{TE1} + I^m_{TM2})\left\{1 + \frac{\sqrt{I^n_{TE1} I^m_{TM2}}}{I^n_{TE1} + I^m_{TM2}} \cos[kL(t) + \phi^{nm}_{TM}]\right\}, \tag{4}$$

where I^m_{TM2} is the intensity of the light reflected by G_2 in Littrow order m when G_2 is illuminated with TM polarization and

$$\phi^{nm}_{TM} = \phi^n_{TE1} - \phi^m_{TM2}, \tag{5}$$

where ϕ^m_{TM2} is the phase difference between the incident field and the field diffracted by G_2 for TM

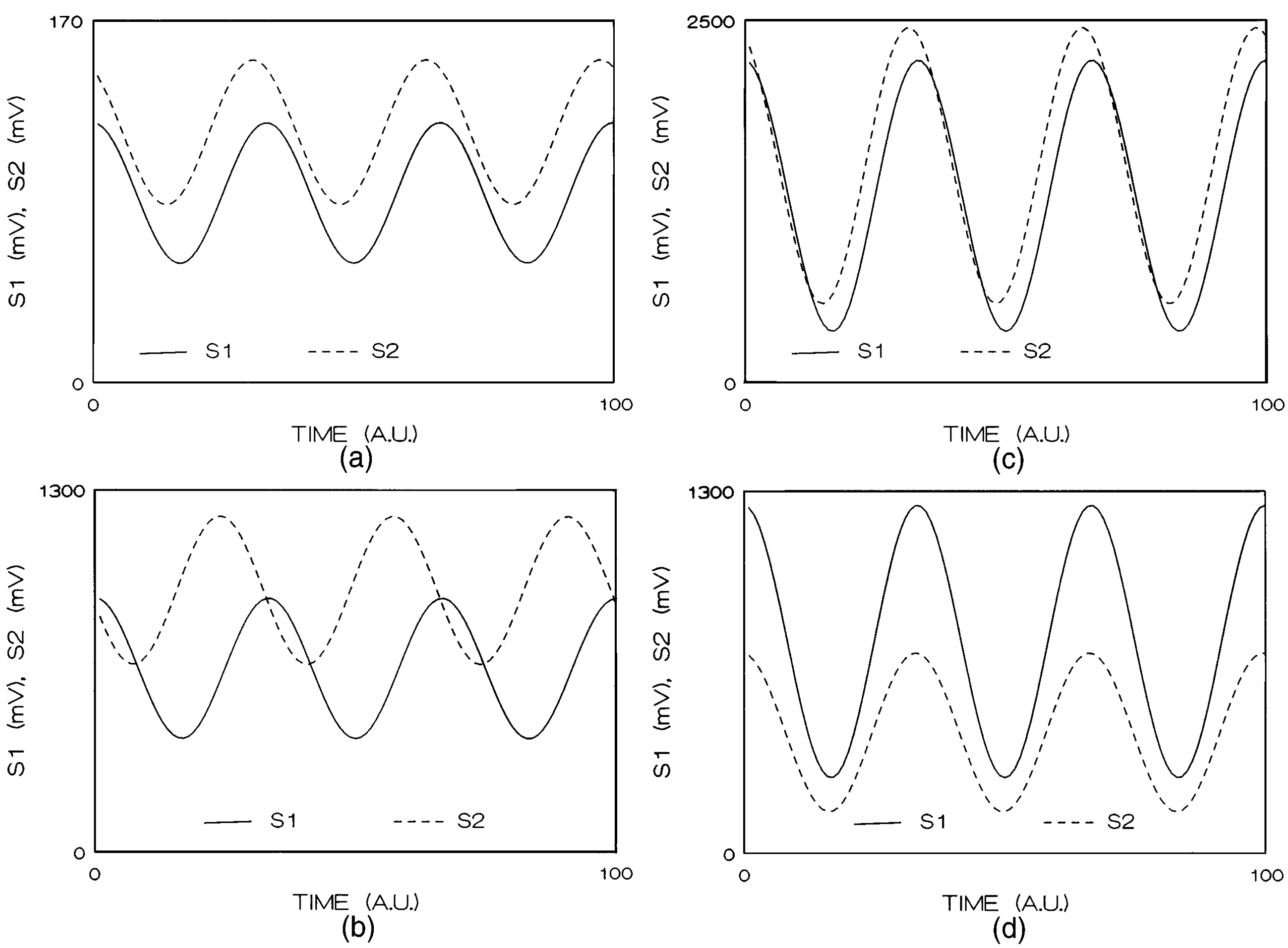

Fig. 2. Signals S1 and S2 as a function of time: (a) G_1 and G_2 are in a Littrow mount for diffracted order $m = -2$ (incidence angle $i = -38.3°$); in this case the grating efficiency is low. (b) G_1 and G_2 are in a Littrow mount for diffracted order $m = -2$ (incidence angle $i = +38.3°$); in this case the grating efficiency is high. (c) G_1 and G_2 are in a Littrow mount for the diffracted order $m = -1$ (incidence angle $i = -18°$); in this case the grating efficiency is high. (d) G_1 and G_2 are in a Littrow mount for the diffracted order $m = -1$ (incidence angle $i = +18°$); in this case the grating efficiency is low.

Table 1. Measurements Obtained from the Experimental Results of Fig. 2

Order m	Incidence Angle (deg)	I_{TE2}/I_0 (%)	I_{TM2}/I_0 (%)	Φ^m (deg)
−2	−38.3	3.5	5.8	28
−2	+38.3	26.4	48.8	100
−1	−18	51.6	68.2	20
−1	+18	30.4	4.3	4
0	0	11.4	0.6	46

polarization. Equations (2) and (4) give Φ^m with

$$\Phi^m = \phi_{TM}^{nm} - \phi_{TE}^{nm}, \tag{6a}$$

$$\Phi^m = \phi_{TE2}^{m} - \phi_{TM2}^{m}, \tag{6b}$$

which is the phase difference between TE and TM polarizations after diffraction by G_2. For a given incidence angle, Φ^m depends only on the optogeometrical characteristics of G_2. Thus the grating interferometer permits Φ^m to be measured. The interference contrast given by the modulation amplitude of S_1 and S_2 permits one to calculate the ratio I_{TM2}^m/I_{TE2}^m. Comparison between the intensity of the incident light I_0 upon the gratings and the continuous backgrounds, $I_{TE2}^n + I_{TE2}^m$ in the first state of C (voltage V_1 applied) and $I_{TE1}^n + I_{TE2}^m$ in the second state of C (voltage V_2 applied), gives the values of the grating efficiencies for an incidence angle corresponding to the Littrow configuration. This measurement can be made for both TE and TM polarizations.

The experimental results obtained with an argon laser emitting at $\lambda_0 = 514.5$ nm and two ruled echelette metallic gratings from Jobin Yvon with a spacing $p \approx 0.83$ μm and a blaze angle $i = 17°27'$ for the wavelength $\lambda_1 = 500$ nm are shown in Fig. 2. Cell C, which is obtained from a Displaytech PV100 shutter, is a half-wave plate for λ_0. The gratings are symmetric with respect to beam splitter BS so that G_1 and G_2 are illuminated with the same incidence angle. In this way the waves that interfere correspond to the same diffraction order ($n = m$). Signals S1 and S2 are recorded as a function of time. The applied voltage on C is changed from V_1 to V_2 between two voltage ramps applied to PZT. The shapes of the gratings used in the experiment are not symmetric, so there are four Littrow orders: two −2 Littrow orders and two −1 Littrow orders for λ_0, which correspond to different grating efficiencies and different values of Φ^m. Figure 2 shows the experimental records of S1 and S2 obtained with $m = -2$ and $m = -1$. The results obtained are given in Table 1. The results obtained when G_2 is used at normal incidence ($m = 0$) are also given in Table 1. To validate the principle of operation, we replaced G_2 by a metallic mirror, and, as expected, no phase variation between S1 and S2 was detected.

In conclusion, we have demonstrated that the described configuration based on a grating interferometer is well suited for the measurement of the phase difference between TE and TM polarizations after diffraction by gratings. Moreover, as in the case with spectroscopic ellipsometers, this configuration is compatible with a scanning wavelength measurement. In this case, a nematic liquid-crystal variable retarder should be used as cell C. The results obtained with a configuration composed of two gratings with nearly the same optogeometrical characteristics have been presented, but the method can be extended to other configurations. However, in order to obtain a high contrast, it is preferable to use a configuration in which the efficiency of G_1 is close to that of G_2. Certainly the proposed scheme does not have the accuracy of a conventional ellipsometer, because the polarization properties (retardation and principal axis rotation) of the liquid-crystal cell are assumed beforehand. For an increase in accuracy, numerical processing of the recorded signals is required. In this case the characteristics of the cell, measured before the experiment, have to be taken into account. Recently the results obtained when a grating interferometer was used as a demodulator for optical fiber sensors with coherence multiplexing were presented.[7] This device, which is well suited for the demodulation of a high number of sensors,[8] suffers from a severe drawback because of the amplitude dependence of the output signal with respect to the optical path differences of the sensors. This effect can make the measurement impossible. The configuration presented here should permit one to solve this problem.

References

1. R. Petit, M. Cadilhac, D. Maystre, P. Vincent, and M. Neviere, in *Electromagnetic Theory of Gratings,* R. Petit, ed., Vol. 22 of Topics in Current Physics (Springer-Verlag, Berlin, 1980), pp. 1–225.
2. D. Maystre, in *Progress in Optics XXI,* E. Wolf, ed. (Elsevier, Amsterdam, 1984), pp. 3–67.
3. M. G. Moharam and T. K. Gaylord, J. Opt. Soc. Am. A **3,** 1780 (1986).
4. P. Vincent, H. Akhouayri, and M. Neviere, J. Opt. Soc. Am. B **8,** 1149 (1991).
5. A. Roger, Opt. Commun. **32,** 11 (1980).
6. P. Connes, Rev. Opt. **38,** 157, 416 (1959); **39,** 402 (1960).
7. H. R. Giovannini, D. Yeddou, S. J. Huard, M. R. Lequime, and C. Froehly, Opt. Lett. **18,** 2074 (1993).
8. M. Lequime, S. Huard, and H. Giovannini, French patent 94402712.7 (November 28, 1994).