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Angle-resolved polarimetric phase measurement for the characterization of gratings

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A goniometric ellipsometer is used to recover the optogeometrical parameters of metallic gratings. The phase difference between TE and TM polarizations in all the diffracted orders is measured as a function of the incidence angle. The groove depth, together with the refractive indices of all the media of the diffracting structure, is determined for a holographic sinusoidal aluminum grating. It is shown that a thin layer of alumina on top of the grating must be considered. © 1996 Optical Society of America

The theory of diffraction by gratings is well known.[1,2] Many experimental studies of grating behavior have been performed, and the results have shown good agreement with those predicted by theory. To characterize their products, grating manufacturers measure the efficiencies in all the diffracted orders as a function of the incidence angle. These measurements allow one to determine the optical properties of gratings, mostly for spectrometric applications. Thanks to the two approaches, experimental and theoretical, it is now possible to realize gratings of high quality with low scattering losses and given optical properties. The techniques of realization of ruled or holographic gratings allow one to obtain many kinds of shape, even for a high number of grooves per millimeter for applications from the x-ray to the microwave domains. To determine theoretically the optogeometrical parameters (shapes, refractive indices) of the gratings one must solve the inverse problem.[3] However, the method described here allows one to make this determination by simply fitting the experimental results to direct theoretical calculations. This problem is of overriding importance when one wants to modify the optical properties of a bare grating by depositing a coating upon it. This well-known technique is used, for example, in the vacuum UV to prevent aluminum gratings from oxidizing. The coating modifies not only the energy distribution in all the diffracted orders but also the corresponding phase differences between TE and TM polarizations. The latter characteristics, usually not used for spectrometric applications, can be used in grating interferometers for optical fiber sensor applications.[4,5] To determine the characteristics (thickness, refractive index) of the coating to be deposited, one must know the optogeometrical parameters of the bare grating. Several techniques, for instance, electron scanning microscopy and atomic force microscopy, can be used to recover the shape. However, only optical measurements allow one to recover both shape and the refractive indices of the diffracting structure. Our experimental method consists of measuring both the grating efficiencies and the corresponding phase differences between TE and TM polarizations as a function of the incidence angle. The latter parameters are interesting, especially near the plasmon resonances, because they are usually much more sensitive to the optogeometrical parameters of the grating than are the efficiencies. This is the key point of this Letter. The efficiencies can be easily measured with a goniometric mounting, whereas the phase measurement requires that one use a device based on an ellipsometer[6] or a grating interferometer.[5] In Refs. 7 and 8 an ellipsometer was used to study the polarization state of the diffracted orders of a metallic grating. However, the authors did not compare their results with those obtained by a rigorous method of computation, and they did not determine the optogeometrical parameters of their gratings. Recently, Cui and Azzam[9] presented results obtained with a normal-incidence rotating-sample ellipsometer. This device was used to measure the ratio of complex reflection coefficients for the two fundamental states of polarization to characterize different gratings. Recent improvements in the differential method allow one to compute the field diffracted by deep metallic gratings.[10] Moreover, this method is well adapted to the study of multilayer structures. Our research differs from preceding studies in that we measure the phase between the two fundamental states of polarization in all the diffracted orders as a function of the incidence angle. In this Letter we show that a method of characterization already used in our laboratory for optical thin-film applications can be useful for the study of diffraction gratings.

The experimental setup used to determine the optical properties of gratings is shown in Fig. 1. The configuration is based on a goniometric ellipsometer–scatterometer.[11,12] The detector can be used to measure the angular pattern of the light diffracted by the grating for the two fundamental cases of polarization. For this first kind of measurement the analyzer is removed. The grating grooves are oriented so that they are perpendicular to the incidence plane. This configuration allows us to measure the grating efficiencies in all the diffracted orders. To vary the incidence angle, we can rotate the grating around a vertical axis parallel to the grooves. The use of the rotating analyzer

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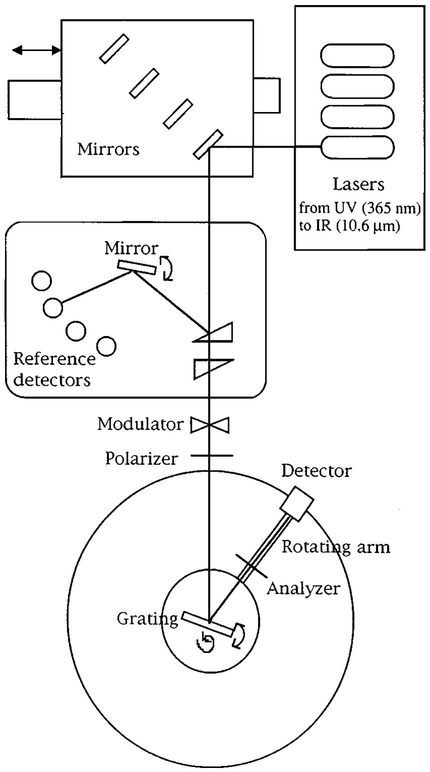


Fig. 1. Schematic of the experimental setup. The mirrors can be translated to select the laser sources. Several detectors can be used, depending on the wavelength of operation. The detector can be rotated around a vertical axis.

allows us to perform an ellipsometric measurement of the light diffracted by the grating. In this case it is possible to measure the phase difference between TE and TM polarizations as a function of the incidence angle. For diffracted order n, the phase difference ϕ_n is given by

$$\phi_n = \arg(B_{n,\mathrm{TE}}) - \arg(B_{n,\mathrm{TM}}), \qquad (1)$$

where $B_{n,\mathrm{TE}}$ and $B_{n,\mathrm{TM}}$ are the complex amplitudes of diffracted order n in air for TE and TM polarizations, respectively, and $\arg(B_n)$ designates the argument of the complex number B_n. ϕ_n can be easily obtained when all the terms of the Rayleigh expansion of the diffracted field are computed. The two detectors, one fixed for reference and the other upon the rotating arm, can be changed depending on the source used. The input light is modulated and the measurements are performed with a lock-in amplifier.

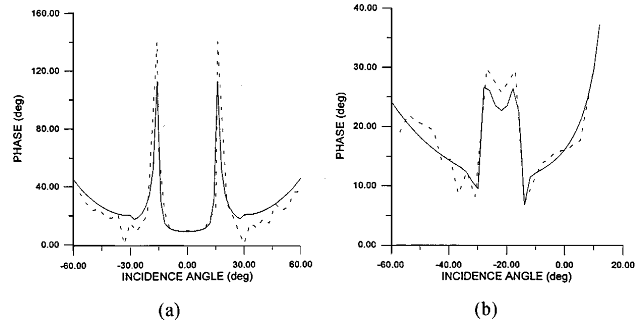
An aluminum grating with 1200 grooves/mm (Milton Roy low-modulation holographic sinusoidal grating) was studied with the device shown in Fig. 1. All the measurements were performed at $\lambda = 0.633\ \mu\mathrm{m}$ with a spot size of 3 mm and a beam divergence of 1 mrad. The number of grooves per millimeter can be easily determined by measurement of the angle between -1 and $+1$ orders in normal incidence. For this parameter, the measurement confirmed the data given by the manufacturer. As it depends on the thickness[13] and the conditions of evaporation, the refractive index of the aluminum layer is much more difficult to recover.

The phase ϕ between TE and TM polarizations was measured as a function of the incidence angle. As was verified experimentally, the efficiency of the $+1$ order is symmetric to that of the -1 order with respect to $\theta = 0$. For this reason, only the results obtained for the 0 and $+1$ orders are presented. We determined the optogeometrical parameters by fitting the experimental results to results given by a numerical simulation based on a rigorous method.[10] To obtain good agreement between the experiment and the numerical approach, one must consider a thin layer of alumina ($\mathrm{Al_2O_3}$) of thickness h_{ox}. Figure 2 shows the results obtained with grating depth $h = 0.111\ \mu\mathrm{m}$ and a refractive index of aluminum $\nu_1 = 1.1 + 9.14j$. One can see the rapid variation of the phases near the plasmon resonances. The refractive index of alumina has been taken as $\nu_{ox} = 1.63$.[13] The value of h is compatible with the data given by the manufacturer, $0.04\ \mu\mathrm{m} < h < 0.125\ \mu\mathrm{m}$. Both real part n and imaginary part k of ν_1 were determined with reflection coefficient $R = 95\%$ for aluminum. This value, which is higher than the values given in the literature for $\lambda = 0.633\ \mu\mathrm{m}$, was obtained by the numerical fit described above. In this case n and k are connected, and k is given by

$$k = [-n^2 - 1 + 2n(1 + R/1 - R)]^{1/2}. \qquad (2)$$

We also measured the efficiencies in all the diffracted orders as a function of the incidence angle by removing the analyzer from the device shown in Fig. 1. Figure 3 shows the results obtained with the parameters given above. The good agreement found between numerical and experimental results confirms the values of the parameters given by the ellipsometric measurements.

In conclusion, we have shown that a method of characterization used in the field of optical thin films can be useful for the study of gratings. This method allows one to determine the optogeometrical parameters of gratings with a relative accuracy of 1%. Moreover, as is done for thin-film applications,[12] this device can also be used to measure the angular pattern of the scattered light out of the direction of the diffracted orders. This measurement should give information about the roughness of the surface of and periodic defects in the shapes of gratings.



(a) (b)

Fig. 2. Phase difference between TE and TM polarizations as a function of the incidence angle. Solid curves, numerical results; dashed curves, experimental results: (a) 0 order, (b) 1 order.

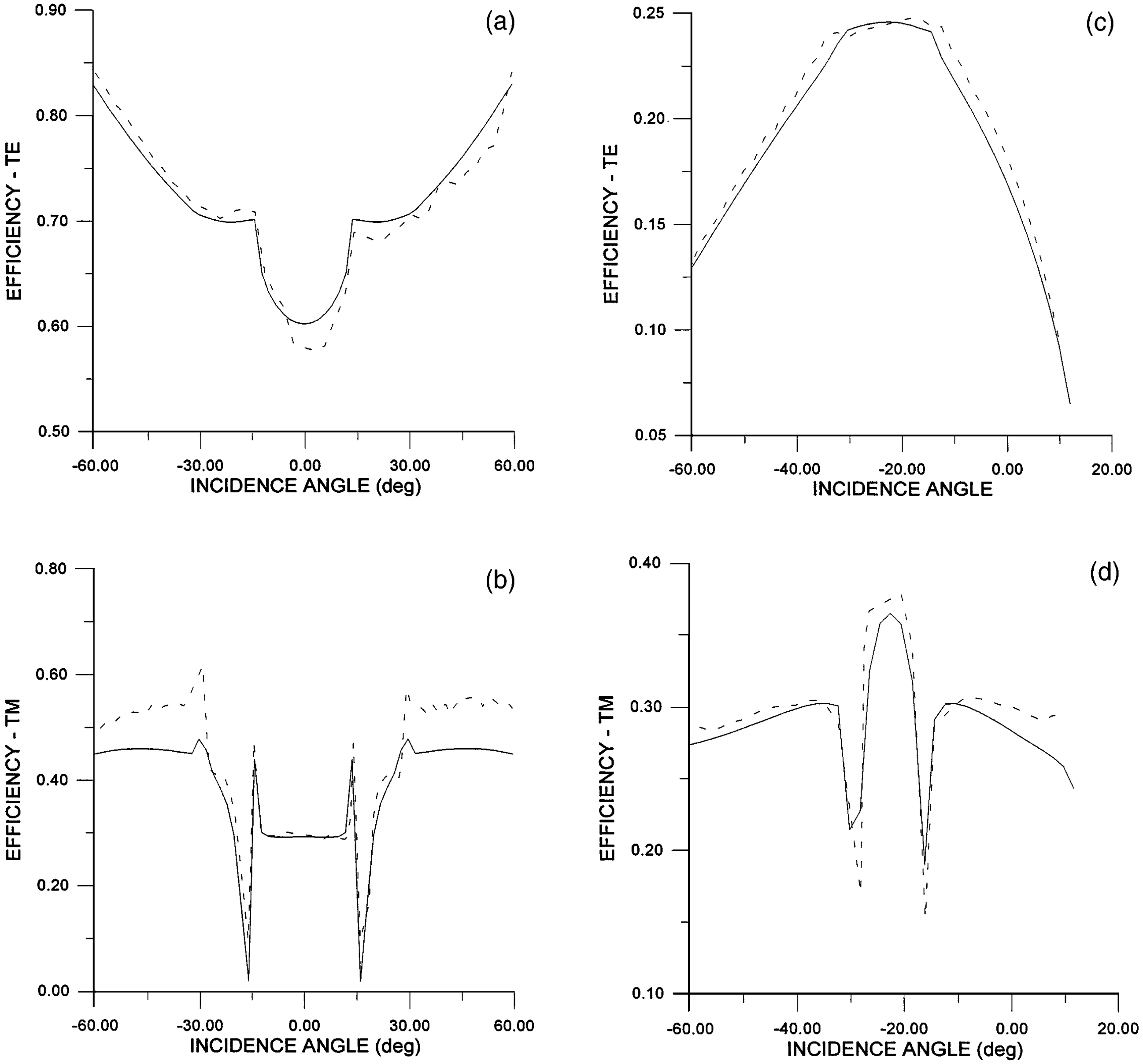


Fig. 3. Efficiencies as a function of the incidence angle. Solid curves, numerical results; dashed curves, experimental results: (a) 0-order TE polarization, (b) 0-order TM polarization, (c) 1-order TE polarization, (d) 1-order TM polarization.

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