Measurement of absolute phase shift on reflection of thin films using white-light spectral interferometry

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A novel method to measure the absolute phase shift on reflection of thin film is presented utilizing a white-light interferometer in spectral domain. By applying Fourier transformation to the recorded spectral interference signal, we retrieve the spectral phase function ϕ, which is induced by three parts: the path length difference in air L, the effective thickness of slightly dispersive cube beam splitter $T_{\rm eff}$ and the nonlinear phase function due to multi-reflection of the thin film structure. We utilize the fact that the overall optical path difference (OPD) is linearly dependent on the refractive index of the beam splitter to determine both L and $T_{\rm eff}$. The spectral phase shift on reflection of thin film structure can be obtained by subtracting these two parts from ϕ. We show theoretically and experimentally that our new method can provide a simple and fast solution in calculating the absolute spectral phase function of optical thin films, while still maintaining high accuracy.

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With the rapid development of optoelectronics industry, demands of optical thin films have been greatly increased. The photometric properties (transmittance, reflectance, and absorptance) are no longer the only concern of optical coatings. Recently, precise knowledge of spectral phase function of thin film begins to play a crucial role, especially in applications such as phase shift masks, reflection-induced phase retarders, and dispersion compensators, etc.[1−5] As the commercial design software and high energy deposition technologies develop, it is nowadays not difficult to design and manufacture thin film filters with phase requirements. Thus, the characterization method of the phase property will dominate whether the final product satisfies the specification. So far, the most two common ways to measure the phase related properties are spectroscopic ellipsometry and white-light interferometry[6−10]. Spectroscopic ellipsometry provides the results of $\phi_{\rm p}-\phi_{\rm s}$ over a wide wavelength range with high precision and accuracy[11]. However, it can only provide the phase shift difference between p and s polarized light instead of the absolute value of $\phi_{\rm p}$ or $\phi_{\rm s}$. White light interferometry has been widely used to measure the group delay of dispersive components, e.g., chirped mirror[3,12−14]. Nevertheless, in this case, the knowledge of the absolute phase shift is not required and the linear part in the overall phase is generally ignored.

In this letter, we present a new technique based on white-light interferometry employing a channeled spectrometer, which provides a simple and fast solution to retrieve the absolute spectral phase function. By applying Fourier transformation to the measured spectral interference signal and filtering out the high-frequency part from the low-frequency one, we could obtain an unwrapped phase function ϕ. Both the path length difference L in air and the effective thickness $T_{\rm eff}$ of the beam splitter (BS) can be determined by using the fact that the overall optical path difference (OPD) is linearly dependent on the refractive index of the BS. Then the spectral phase shift on reflection of the thin film structure can be obtained by subtracting these two parts from ϕ. We confirm the feasibility of our method by showing good agreements between theoretical data and experimental ones of four single-layer samples.

Consider a classical uncompensated Michelson interferometer with a broadband white-light source and a channeled spectrometer, as shown in Fig. 1. It consists of a tungsten halogen lamp, two collimating lenses, a 50/50 BS made of BK7, micropositioners (connected to the sample film and reference mirror respectively), and a fiber-optic spectrometer USB4000 (Ocean Optics) which uses linear charge-coupled device (CCD) array detectors with 3648 pixels and a 600-line/mm diffraction grating with blazing wavelength at 500 nm[15]. The operation range is from 200 to 1100 nm, and the input and output focus lengths are 42 and 68 mm, respectively. The spectral resolution is given with full-width at half-maximum (FWHM) between 0.3 and 10 nm, depending on the core diameter of the read fiber, which in our case is 1 nm. The light beam emitted from the tungsten halogen lamp is first collimated by a lens and then incident on the BS. It is separated into two parts: one to the reference mirror and the other to the sample. The two reflected beams are combined to interfere after passing through the splitter again. The light is finally coupled into the entrance fiber and the interference signal is recorded by the spectrometer. We also set the integrated time as 8 ms and average times as 5 to get better performance. The interference signal recorded in the output of USB4000 is shown as Fig. 2. For an uncompensated Michelson interferometer, the two geometric paths of light in the BS between two arms are not equal. So the asymmetric BS can be replaced by an ideal symmetric one and a plate of the same material with an effective thickness $T_{\rm eff}$.

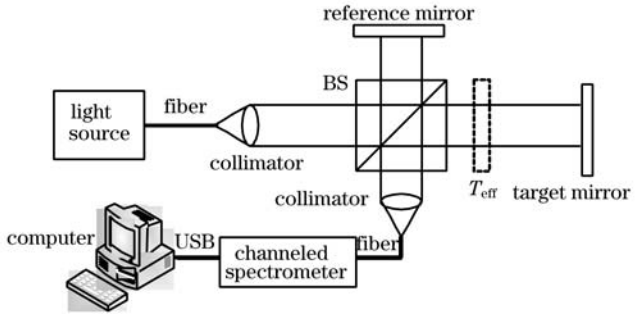

Fig. 1. Dispersive white-light interferometer to measure nonlinear phase function with thin film on the sample arm.

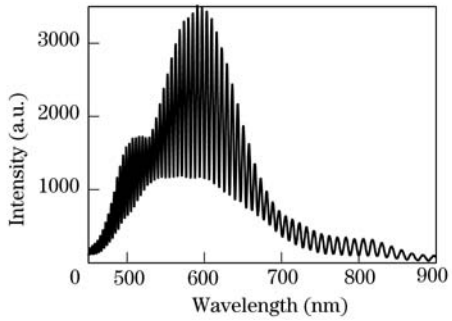

Fig. 2. Interference signal recoded in the output of USB4000 spectrometer.

For a channeled spectrometer with Gaussian response function, the fringe pattern measured at the output of USB4000 can be expressed as

$$I(\lambda) = I_0(\lambda)\left\{1 + V(\lambda)\cos\left[\frac{2\pi}{\lambda}\Delta(\lambda)\right]\right\}, \tag{1}$$

where $I_0(\lambda)$ is the reference spectrum, $V(\lambda)$ is the visibility term related to the interference fringe, $\Delta(\lambda)$ is the OPD between two arms of the interferometer expressed by

$$\Delta(\lambda) = 2L + 2n_{\text{bs}}(\lambda)T_{\text{eff}} - \delta(\lambda)\lambda/2\pi, \tag{2}$$

where $n_{\text{bs}}(\lambda)$ is the refractive index of the BS, $\delta(\lambda)$ is the nonlinear part induced by the reflection on thin film structure, i.e., the phase shift on reflection we desire to know.

Note that Eq. (1) can also be expressed as

$$\begin{aligned} G(\lambda) &= a(\lambda) + b(\lambda)\cos(\varphi(\lambda)) \\ &= a(\lambda) + \frac{1}{2}b(\lambda)\exp(\varphi(\lambda)\mathrm{i}) \\ &\quad + \frac{1}{2}b^*(\lambda)\exp(-\varphi(\lambda)\mathrm{i}), \end{aligned} \tag{3}$$

where $a(\lambda)$ and $b(\lambda)$ represent background spectrum and interference envelop term respectively, $b^*(\lambda)$ is the conjugate value of $b(\lambda)$ and $\varphi(\lambda)$ is the spectral phase function including three parts as mentioned above. In most cases, $a(\lambda)$ and $b(\lambda)$ vary slowly compared with $\varphi(\lambda)$.

$\varphi(\lambda)$ can be obtained from interference fringe by the following procedure. First, the interference signal is processed by fast Fourier transformation. From Eq. (3), it can be expressed as

$$G(f) = A(f) + B(f - f_0) + B^*(f + f_0), \tag{4}$$

where capital letters denote Fourier spectrum, f indicates the spectral variable of the wavelength λ, and f_0 is called spectral carrier frequency. Because of the existence of f_0, the three parts of Fourier spectrum can be easily separated, as shown in Fig. 3. $B(f - f_0)$ can be filtered out from $G(f)$ by using a window function. Next, we compute the inverse Fourier transformation of $B(f - f_0)$ with respect to f and obtain $c(\lambda)$ defined by

$$c(\lambda) = b(\lambda)\exp[\varphi(\lambda)\mathrm{i}]. \tag{5}$$

Here $\varphi(\lambda)$ means Fourier phase of $c(\lambda)$, defined by

$$\tan[\varphi(\lambda)] = \frac{\mathrm{Im}[c(\lambda)]}{\mathrm{Re}[c(\lambda)]}. \tag{6}$$

Since $\tan^{-1}(x)$ is between $-\pi$ and π, various methods could be used to retrieve the unwrapped phase. Notice that $\varphi(\lambda)$ here still has the ambiguity of $2m\pi$ (where m is an integer) because of the initial phase shift.

The ambiguity m could be removed by using the fact that the OPD is linearly dependent on the refractive index $n_{\text{bs}}(\lambda)$ and the spectral phase function of the sample under test $\delta(\lambda)$ is highly nonlinear, which can be concluded from Eq. (2). We determine the initial interference order m by the following procedure. For a reasonable range of m (from -300 to 300), fit $\Delta(\lambda)$ as a linear function of $n_{\text{bs}}(\lambda)$ at each m using least square algorithm and find m when $\Delta(\lambda)$ and $n_{\text{bs}}(\lambda)$ get the best linearity, as shown in Fig. 4. Note that the dotted line in Fig. 4 denotes the experimental data and the solid line denotes the linear fitted value, from which we can get T_{eff} as the slope and L as the intercept. Knowing all of L, $\Delta(\lambda)$, and T_{eff}, we could easily retrieve the spectral phase function $n_{\text{bs}}(\lambda)$ by simple calculation using Eq. (2).

By using the method mentioned above, we could retrieve the spectral phase function $\delta(\lambda)$ without knowing the concrete structure or refractive index of thin film layers on the sample arm. That means it can be applied to either single layer or multi-layers. Here we take single-layer films as examples. Let $\phi^m(\lambda)$ be the experimental data of phase distribution computed with our method, and $\phi^{\text{th}}(\lambda, d)$ be the theoretical value calculated as

$$\varphi^{\text{th}}(\lambda, d) = \text{angle}\left[\frac{r_{01} + r_{12}\exp(-\mathrm{i}2\beta)}{1 + r_{01}r_{12}\exp(-\mathrm{i}2\beta)}\right], \tag{7}$$

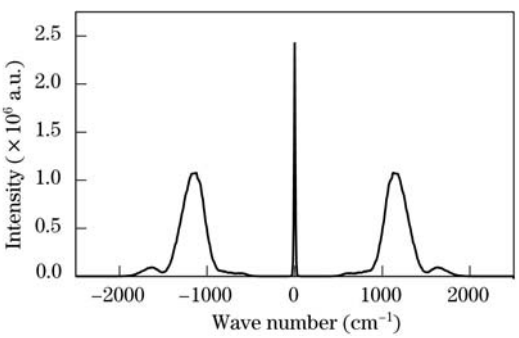

Fig. 3. Fourier transformation of the spectrum signal.

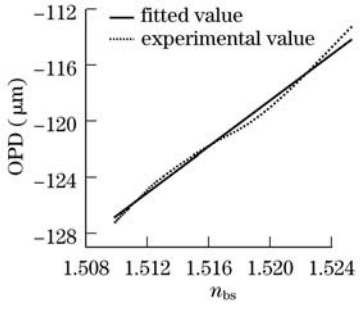

Fig. 4. Linear fitting for $\Delta(\lambda)$ and $n_{\rm bs}(\lambda)$. The deviation between two curves is due to the nonlinear part $\delta(\lambda)$ introduced by the sample film.

where r_{01} and r_{12} represent the Fresnel reflection coefficients of the top and bottom boundaries of the film, respectively, and β denotes the phase change that the reflected wave experiences as it traverses the thin-film layer once from one boundary to the other, which can be expressed as

$$\beta = 2\pi n(\lambda) d\cos\theta/\lambda, \tag{8}$$

where $n(\lambda)$ and d are the refractive index and thickness of the thin film, and θ denotes the propagation angle of incident beam. The well-known Cauchy equation is used to determine $n(\lambda)$.

The photometric method is used to determine d and $n(\lambda)$ based on the Cauthy formula. Then the theoretical phase shift $\phi^{\rm th}(\lambda, d)$ can be calculated from Eq. (8). Figures 5(a)–(d) show both the experimental and theoretical phase functions of four single-layer TiO_2 samples with different thicknesses. Multiple-scan averaging of the interference signal and data smoothing method are used to make better performance. It can be seen from all the figures that there is a good agreement between theoretical and experimental values with the error less than 0.5% between 480 and 700 nm. However, there exists relatively larger deviation around the short- and long-wave bands (especially between 780 and 850 nm) due to the low intensity of light source as well as the low response sensitivity of CCD detector in this spectral range. We can also use this method to retrieve the thickness d of single layer by fitting the recorded interference pattern provided that the optical constants of material are known. It should also be noticed that the method is on the assumption that the information of the sample layer (such as the number of layers, refractive index, thickness) is totally unknown. Therefore, it can be used both for single layer and multi-layers. The study on the measurement of multi-layer thin films filter is in progress.

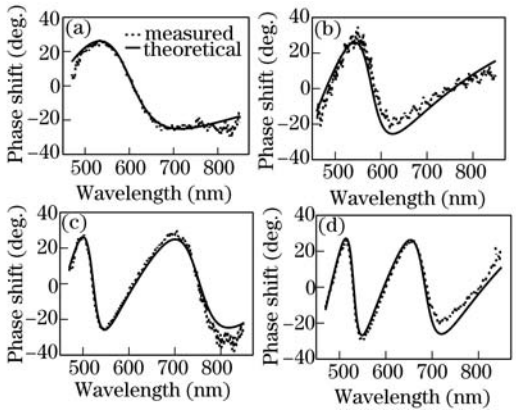

Fig. 5. Comparisons between the experimental and theoretical phase functions of four single-layer TiO_2 samples with different thicknesses. (a) 150 nm, (b) 260 nm, (c) 380 nm, (d) 460 nm.

In conclusion, a new method for evaluating the absolute phase shift of thin film is proposed and experimentally demonstrated. It utilizes Fourier transformation of the interference signal and extracts the high frequency part that contains the useful phase information, which is proved to be a simple, fast, and accurate solution for the retrieval of absolute spectral phase function of optical thin films. This method is useful for phase calculation for both single-layer and multi-layers, and can be extended for the dispersion evaluation, such as the study of group delay and group delay dispersion.

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