Dispersive white-light spectral interferometer for optical properties measurement of optical thin films

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A dispersive white-light spectral interferometer for precise measurements of the phase properties of multilayer thin film structures is built. A novel wavelet-based differentiation approach that considerably resists measurement error of group delay (GD) and group delay dispersion (GDD) is introduced. Versatile applications beyond phase measurement of the apparatus are demonstrated, including piezoelectric coefficient determination and physical thickness retrieval. With the increase of demand for thin film structures with specific phase properties, this white-light spectral interferometer can play an important role in future thin film industry.

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The rapid development of the optoelectronics industry has greatly increased the demand for optical thin films. Thin film structures with specific phase properties such as phase shift mask, reflection-induced phase retarder, dispersion compensator, and others are playing a crucial role in nulling interferometry, optical communication, and femtosecond laser system[1]. Thus, a precise measurement apparatus is required for the determination of the phase properties $\varphi(w)$, as well as the first and second derivatives, namely, group delay (GD) ($\mathrm{GD}(w){=}-\frac{\mathrm{d}\varphi(w)}{\mathrm{d}w}$) and group delay dispersion (GDD) ($\mathrm{GDD}(w) = -\frac{\partial^2\varphi(w)}{\partial w^2}$), with respect to frequency w, the standard phase measurement method, can be divided into several sub-categories: the spectrally integrated method[2−4], the spectrally resolved method[1,5], and the scanning spectrally resolved method[6]. Among these methods, the spectrally resolved method enjoys the distinct advantage of being able to determine the phase properties for each wavelength correspondingly and directly. The apparatus needed is also relatively easier to build with the aid of a commercial spectrometer. In this letter, such an apparatus is built for phase measurement of the thin film structures, and its versatile application potential for various measurement tasks, including thin film thickness retrieval and piezoelectric coefficient determination, are demonstrated.

As shown in Fig. 1, the proposed measurement system consists of a tungsten halogen lamp, two collimation lens, a 50/50 BK7 glass beam splitter, a polarizer employed to eliminate the interference effect in the beam splitter, two micropositioners connecting to the sample film and reference mirror, and a fiber-optic spectrometer (USB4000, Ocean Optics). The emitted light beam from the tungsten halogen lamp is first collimated by a lens. It is then separated into two parts, wherein one goes to the reference mirror and the other to the sample. The interferograms of the two reflective lights are recorded by the spectrometer, then processed by a computer.

In a previous study, we have demonstrated the application of the appratus for precise measurement of thin film reflective phase properties[3]. However, it is much more difficult to determine the GD and GDD properties since the retrieval phase must be differentiated once and twice, respectively. Any measurement error would be magnified in the common numerical differentiation process, resulting in unwanted oscillations on the GD and GDD curves. To eliminate this detrimental effect, the moving average smoothing and polynomial function fitting method is used to smooth the phase properties prior to differentiation. Nevertheless, the de-noising effect of the moving average is limited and might distort the GD when the phase properties change too fast. The polynomial function fitting cannot be used in analyzing complicated phase properties of thin film structures. Here, we introduce a novel derivation calculation based on wavelet transformation featuring resistance to measurement errors. In recent years, this approach has been successfully applied in analytical chemistry[7] and ultrasound elastography[8].

The continuous wavelet transform (CWT) of the retrieval phase $\varphi_{\text{thin film}}(w)$ is defined as

$$\mathrm{CWT}(w',\varpi) = \int_{-\infty}^{+\infty} \varphi_{\text{thin film}}(w)\frac{1}{\sqrt{\varpi}}\,\psi\left(\frac{w-w'}{\varpi}\right)\mathrm{d}w, \tag{1}$$

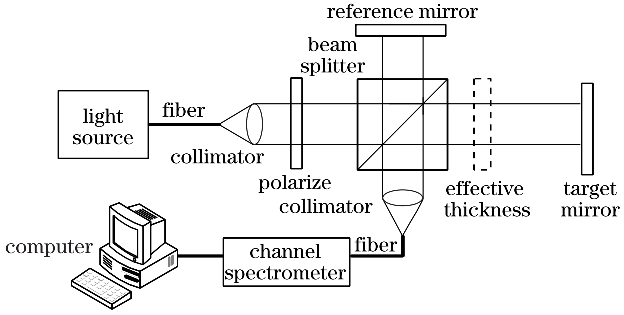

Fig. 1. Schematic of the dispersive white-light interferometers.

where w' and ϖ are the shift factor and dilation factor, respectively. $\psi(w)$ is a mother wavelet function and $\psi(\frac{w-w'}{\varpi})$ is the daughter wavelet function. The mother wavelet function $\psi(w)$ is defined as the derivative of a smoothing function $\theta(w)$, which has a fast decay and a nonzero constant integral

$$\int_{-\infty}^{+\infty} \theta(w)\mathrm{d}w = \Phi(x)|_{x=0} = K \neq 0, \qquad (2)$$

where $\Phi(x)$ is the Fourier transform of $\theta(w)$.

It has been proven[7,8] that $\mathrm{CWT}(w', \varpi)$ with the above wavelet function is the derivative of the signal smoothed by a weighted average kernel $\theta(w)$ dilated through ϖ, weighted by $\frac{1}{\sqrt{\varpi}}$, and scanned through w'. Its relationship with the derivation is given by

$$\lim_{\varpi \to 0} \left. \frac{\mathrm{CWT}(w', \varpi)}{K\varpi^{3/2}} \right|_{w'=w} = \frac{\mathrm{d}\varphi(w)}{\mathrm{d}w} = -\mathrm{GD}(w). \qquad (3)$$

Accordingly, the CWT has the combined properties of data smoothing and differentiation. The GD and GDD properties are retrieved based on this approach.

Before phase measurement, some experiments must be conducted to determine and calibrate the intrinsic measurement errors of the apparatus. This can be accomplished by the measurement of a structure with known dispersion properties. First, two identical thin metal films (Ag) are placed on both arms, which would theoretically induce zero GD. As shown in Fig. 2(a), the measured GD properties within ±1 fs fit the theoretical result well. The second experiment measures the group delay of a bulk material (2.046-μm BK7), whose theoretical group delay properties can be calculated from a Sellimier formula. The measurement results match the theoretical one very well, with a small discrepancy of less than 3 fs (Fig. 2(b)). Thus, both experiments prove the high accuracy of our apparatus.

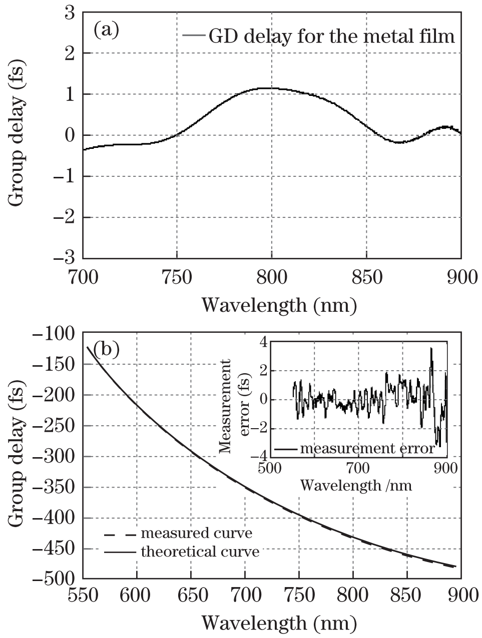

Fig. 2. Calibration of the system for accuracy measurement (a) measured GD properties for identical metal film; (b) measured and theoretical GD properties for bulk material.

Next, the GDD properties of the home-made chirped mirror (CM) based on our apparatus are measured. In recent years, CMs have been widely applied for dispersion compensation in ultrafast laser systems. The accurate measurement of GDD properties plays a crucial role for precise characterization and manufacturing of such a device. The measurement process can be divided into two separate steps. Firstly, two identical metallic mirrors are placed on the two arms of the interferometer for measuring the intrinsic phase difference of the system. This can be induced by the difference of the two arms, as well as the unbalanced beam splitter. Secondly, one of the metallic mirrors is replaced by the test sample, and the GD and GDD invoked by the sample are measured. The GD generated by the common differentiation method with our wavelet-based differentiation method is compared in Fig. 3(a). The noise of the common differentiation is so great that it is difficult to evaluate if they are from the measurement noise or from real phase. If differentiated once more to determine the GDD properties, the noise would be even more unbearable; the GD retrieved by our method is much smoother. In Fig. 3(b), this measurement result is compared with the designed GDD property. A certain degree of discrepancy between the two curves indicates the fabrication errors of the CM. To further prove the robustness of our apparatus, CM is measured several times with different balance positions, and the measured GDD is proven consistent within a certain range.

The application of our apparatus is not limited to the measurement the phase properties, but can be used to measure other phase-related properties. One case in point is the determination of the piezoelectric coefficient of the piezoelectric thin films. This structure can be used

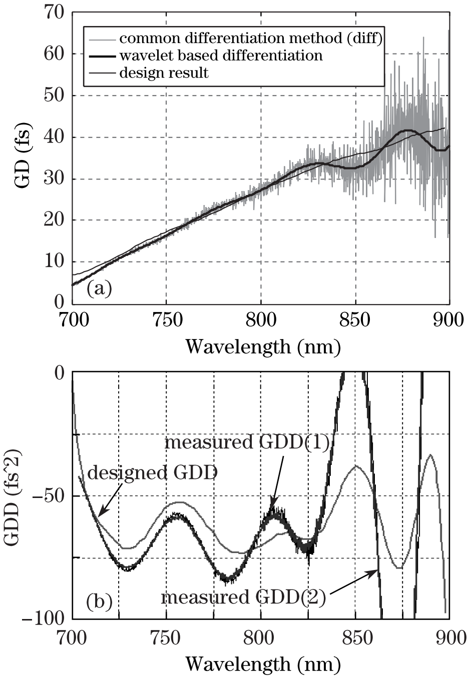

Fig. 3. (a) Comparison of designed and measured GD curves with different method and (b) comparison of designed and measured GDD curve at different positions.

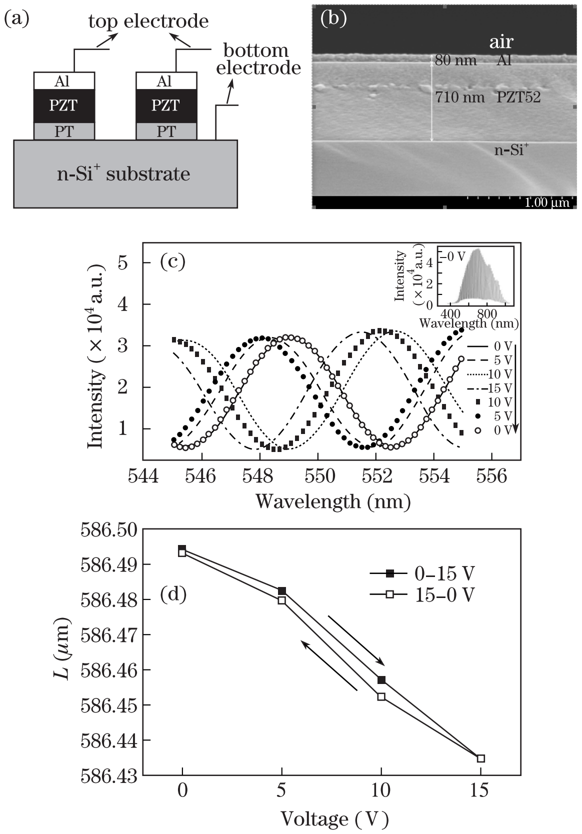

Fig. 4. Measurement of piezoelectric thin film structure. (a) Schematic of the micro reflective mirror matrix (after etching), (b) scanning electron microscope SEM showing the intersection of the structure, (c) recorded interferogram for piezoelectric ceramic (PZT) undergo different volts, and (d) retrieved thickness variation.

as a tunable filter or deformable mirror in micro-opto-electro-mechanical systems (MOEMS), the piezoelectric coefficient of which needs to be measured precisely. Here, a home-made Pb(Zr52Ti48)O3(PZT52) reflective mirror (Figs. 4(a) and (b)) is measured on our apparatus, and the recorded interferogram is shown in Fig. 4(c). When different volts are applied to the reflective mirror, the thin film thickness changes, inducing a small variation of the total OPD, which manifests on the recorded interferogram. By careful analysis of the interferogram, the change in thin film thickness can be measured under different voltages, and the piezoelectric coefficient can be determined, as shown in Fig. 4(d). Compared with commercial white-light interferometer profilometry, our apparatus offers a convenient approach for *in situ* measurement of the change in thickness of the thin film within a specific small area.

Another application of our apparatus is the retrieval of the physical thickness of thin films, which is a fundamental measurement task in the thin film industry. Since both the recorded interferogram and the measured phase properties are strongly related to the physical thickness, either the recorded interferogram or the measured phase properties can be fitted to retrieve the phase properties. A single layer of TiO_2 deposited on the glass substrate is measured. The fitted theoretical results match the measured ones very well, as shown in Fig. 5. To further demonstrate the validity of the retrieved thickness, the results are compared with others determined by photometry, as shown in Table 1. The difference between the two methods is very small (< 2 nm). Our white-light interferometry apparatus thus offers a new way to determine the physical thickness.

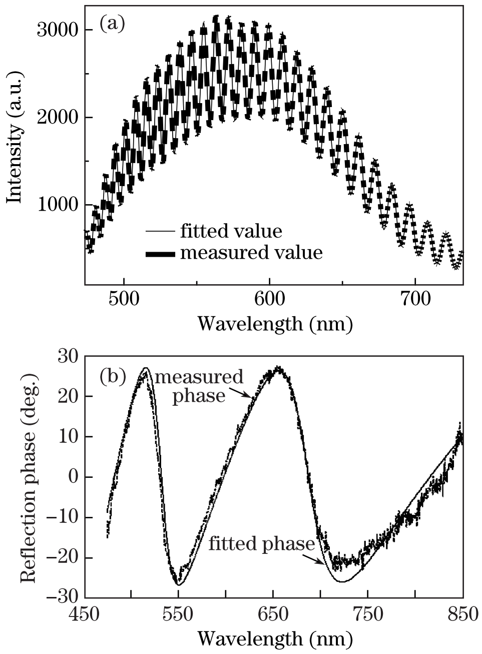

Fig. 5. Retrieval of thin film thickness. (a) Fitting the recorded interferogram, (b) by fitting the measured phase.

Table 1. Thickness Test for TiO_2 with Photometry and White-Light Interferometry

Thin film under test	Determined by white-light interferometry (nm)	Determined by photometry (nm)
No.1	262.8	264
No.2	363.5	364.5
No.3	462.5	461.1

In conclusion, a white-light interferometry apparatus is developed for precisely measuring the phase properties, as well as the GD and GDD properties, of thin film structure. A novel wavelet-based differentiation approach with considerable resistance to measurement error is introduced. Versatile applications of the apparatus such as the piezoelectric coefficient determination and the physical thickness retrieval are demonstrated. Thus, the apparatus is a very promising tool for the future of the thin film industry. More works to expand its applications and further refinement of the apparatus are in process.

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