

# Preparation of high performance thin-film polarizers

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The optical performance of thin film polarizers is highly sensitive to the layer thicknesses of thin film. The thicknesses of the sensitive layers are optimized in order to gain broader polarizing zone in such case when the total layer thickness does not increase. An automatic layer thickness control system is established, and errors caused by different monitoring methods are analyzed. With this thickness control system, thin-film polarizers with  $T_p$  higher than 98% and  $T_p/T_s$  higher than 200:1 ( $T_p$  and  $T_s$  are transmissions for p- and s-polarizations, respectively) with the bandwidth of 11 nm are prepared. Using the system allows for optimum repeatability of three successive runs.

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Since the application of thin-film polarizers in large laser systems in the 1970s, their performance has created great impact on the entire laser system. As essential components of the system, they switch the beam out of the primary laser cavity and provide a well-defined linear polarization for frequency conversion which protects the system from back-reflected light. This means that the polarizers should possess high transmission of p-polarization ( $T_p$ ) and high contrast ratio  $T_p/T_s$ , where  $T_s$  is transmission of s-polarization. The preparation of a high performance thin-film polarizer is important for the large laser system to receive beam light with high efficiency and good quality. However, the polarizer usually has more than 30 layers and its performance is very sensitive to the thickness of thin film, especially to the thickness of some sensitive layers. Therefore, the parameters from coating design to preparation, and the technology applied in monitoring layer thickness should be strictly controlled<sup>[1-5]</sup>, since an accurate and reliable layer thickness monitoring system is essential in preparing a polarizer.

In this letter, the thicknesses of sensitive layers of a quarter wave design are optimized in order to gain broader polarizing zone without increasing the total film thickness. An automatic thickness control system is established, by which both quarter-wave and non-quarter-wave coatings can be monitored. With this thickness control system, thin-film polarizers with  $T_p$  exceeding 98% and  $T_p/T_s$  higher than 200:1 with the bandwidth of 11 nm are prepared, achieving a considerably optimized repeatability of three successive runs.

The principle of a Brewster's angle thin-film polarizer is based on the following theory: the width of the high-reflectance zone of a quarter-wave stack is a function of the ratio of the admittances of the high refractive index ( $n_H$ ) and low refractive index ( $n_L$ ) materials; this ratio varies with the incident angle  $\theta$  and is different for s- and p-polarized lights:

$$\eta_s = n \cos \theta, \tag{1}$$

$$\eta_p = n / \cos \theta, \tag{2}$$

where  $\eta_s$  and  $\eta_p$  are the admittance of s- and p-polarizations, respectively. So,

$$\eta_{Hs} / \eta_{Ls} = \cos \theta_H / \cos \theta_L, \tag{3}$$

$$\eta_{Hp} / \eta_{Lp} = \cos \theta_L / \cos \theta_H, \tag{4}$$

where H and L represent the high refractive index material and low refractive index material, respectively.

Therefore,

$$\frac{(\eta_H / \eta_L)_s}{(\eta_H / \eta_L)_p} = \frac{(\cos \theta_H)^2}{(\cos \theta_L)^2}, \tag{5}$$

where the factor  $(\cos \theta_H)^2 / (\cos \theta_L)^2$  is always more than a unit, which means that the width of the high-reflectance zone for p-polarized light is always less than that for s-polarized light. Within the region inside the s-polarization but outside the p-polarization high-reflectance zone, the reflectance is high for s-polarization but low for p-polarization, which means that the component acts as a polarizer. In fact, any coating with a sharp edge between transmittance and reflectance can potentially be used as a polarizer<sup>[6,7]</sup>.

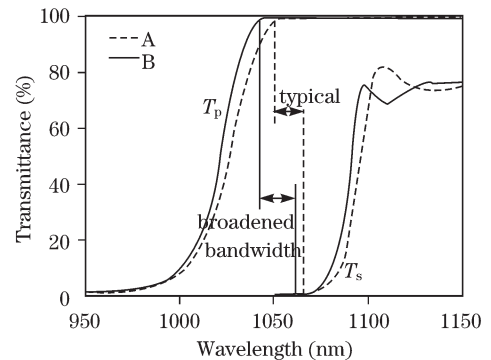


Fig. 1. Theoretical performance of (A) quarter-wave thin film polarizer and (B) broadened polarizer with non-quarter-wave layers.

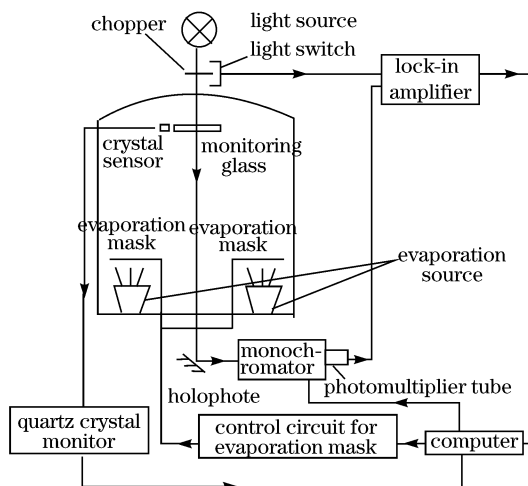


Fig. 2. Schematic of the automatic thickness control system.

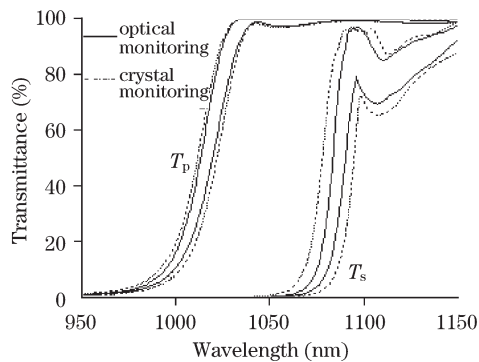


Fig. 3. Theoretical performance envelope curves of the polarizer.

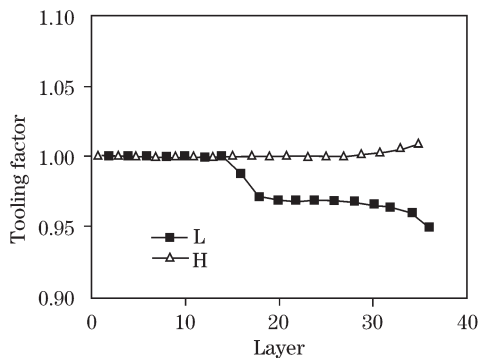


Fig. 4. Dynamic crystal correction for changing crystal performance as a function of deposited material on the surface.

Hafnia ( $\text{HfO}_2$ ) and silica oxide ( $\text{SiO}_2$ ) were chosen as coating materials considering their current commercial usage<sup>[1,8,9]</sup>. The high-reflectance zone of a quarter-wave stack becomes wider as the total layer thickness increases. However, the actual layer thickness should be limited because of the source depletion and the accumulated error, which might contribute to the failure of coating<sup>[1]</sup>. In order to gain broader polarizing zone without increasing the total layer thickness, a 36-layer quarter-wave stack was designed, and the thicknesses of sensitive layers were optimized. As shown in Fig. 1, the polarization zone of  $T_p$  higher than 98% and  $T_p/T_s$  more than 200:1 increase from 11 to 19 nm after the thickness of sensitive layers are optimized.

A reliable and accurate thickness control system is also essential for preparing high performance coatings. For a coating machine, in which the layer thickness is manually controlled, the accuracy and the repeatability are not good enough for preparing high performance coatings, such as thin film polarizers. Hence, there is a need to build an automatic thickness control system for the coating machine. As shown in Fig. 2, continuous wave (CW) halogen light is chopped into pulsed light, and then allowed to pass through a monitoring glass and a monochromator, before finally receiving a photomultiplier. A lock-in amplifier is used to detect the photomultiplier signal. A light switch is used to acquire the frequency of the chopped light, and the obtained frequency is used as the reference frequency of the lock-in amplifier. Quartz crystal sensor is installed beside the monitoring glass. The lock-in amplifier, quartz crystal monitor, and monochromator are all connected to a computer through an RS232 port; data are analyzed and processed by self-programmed software<sup>[10]</sup>. The software can send a signal to the evaporation mask control circuit, and automatically turn it off at the cutting point. With the lock-in amplifier and quartz crystal monitor, the automatic thickness control system can cut off layers by both optical and quartz crystal methods.

Optical and quartz crystal methods are more commonly used for monitoring film thickness<sup>[11]</sup>. Each method has its unique advantages. For example, the optical turning point monitoring method is commonly used to monitor quarter-wave coatings; it provides the direct measurement of the optical thickness and can compensate for film thickness when thickness monitoring error occurs. However, it is sensitive to the effect of noise to the signal and the long time stability of the optical monitoring signal. In addition, it is not highly compatible with ultra-thin layer deposition and non-quarter-wave coatings. On the other hand, quartz crystal monitoring can precisely control the mass thickness of thin film and is suitable for both thin and thick layers. However, it cannot provide the direct measurement of optical thickness. We analyzed the errors for these two monitoring methods by assuming that the uniformly distributed optical thickness error of each layer was 1% for the optical turning point monitoring method, and that the physical thickness error of each layer was less than 2 nm for the quartz crystal monitoring. The relative refractive index error was at 1%, and the errors were found to be uniformly distributed. As shown in Fig. 3, the curves in solid and dash dot lines correspond to the theoretical performance envelope curves for the optical turning point and the quartz crystal monitoring methods, respectively. The solid lines are surrounded by the dash dot lines, demonstrating that the deviation of the spectrum is smaller when the optical turning point monitoring method is used.

We optimized several layers to be non-quarter-wave layers, which caused the optimized layers and the following layers not to be monitored by the optical turning point method. However, the quartz crystal monitor measured the physical thickness of thin film deposited on the quartz crystal sensor, and the optical thickness of thin film equalled the refractive index of material multiple physical thickness. Hence, the tooling factor of

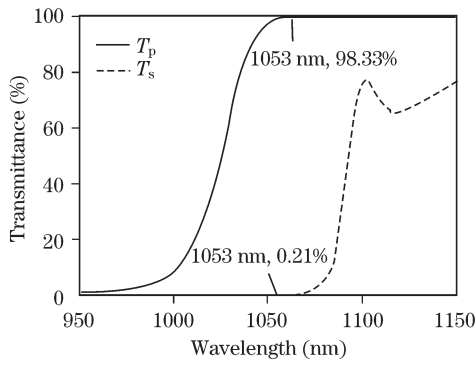


Fig. 5. Measured spectra of the polarizer with the incident angle of 56.5°.

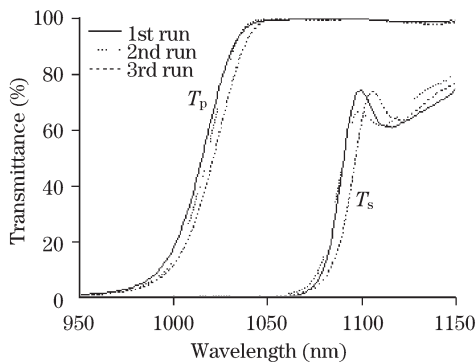


Fig. 6. Polarizer spectra of three successive runs.

quartz crystal can easily be affected by process parameters, such as deposition temperature, deposition rate, and O<sub>2</sub> gas flow quantity, since the refractive index of material changes with these parameters. For these reasons, the optical turning point monitoring and the quartz crystal monitoring were both adjusted to control the layer thickness. On one hand, the non-quarter-wave and the subsequent layers were controlled by the quartz crystal; on the other hand, the layers before the non-quarter-wave layers were monitored by the turning point monitoring method. Meanwhile, the thickness of each layer acquired by the quartz crystal monitor was recorded and used to calibrate the tooling factor.

The tooling factor of the quartz crystal monitoring speaks of the location of the quartz crystal sensor head and substrate. Nevertheless, as coating built up on the quartz crystal, the performance of the crystal changed due to induced stress, leading to a change in the calibration of the tooling factor as a function of film thickness. In order to control the layer thickness accurately, the calibration should be made.

In this letter, a coating was prepared. Its thickness could be determined by the quartz crystal monitor when there is no calibration to the tooling factor. The spectrum was measured at a normal angle by Lambda 900 spectrophotometer, while the actual film thickness of each layer was acquired by the inverse of the measured spectrum using the TFCalc software. The calibration factor of each layer equaled the theoretical thickness divided by the simulated actual thickness of each layer

(Fig. 4). The calibration was used to correct the thickness targets on the quartz crystal monitor to achieve the desired thickness on substrates.

Electron-beam gun evaporation was used to deposit the 36-layer coatings, while the automatic thickness control system was used to monitor the layer thickness. The thin-film polarizer was made with ZZSX-1800 coating machine, and HfO<sub>2</sub> and SiO<sub>2</sub> were chosen as coating materials. The deposition rates of HfO<sub>2</sub> and SiO<sub>2</sub> were about 0.2 and 0.4 nm/s, respectively; the deposition pressure was 2×10<sup>-2</sup> Pa, and the heating temperature was 200 °C. In order to avoid losing the oxygen of coating materials, O<sub>2</sub> was used as the working gas, and the gas flow was adjusted automatically to maintain a stable deposition pressure.

The Lambda 900 spectrophotometer was used to measure the photometric performance of the polarizer, with the incident angle of 56.5°. As shown in Fig. 5, the photometric performance is remarkably good, with the polarizing zone being about 11 nm ( $T_p > 98\%$  and  $T_p/T_s > 200$ ).

In order to test the stability of this monitoring system, three successive runs were made. The spectra of substrates at the same position of each coating were measured (Fig. 6), depicting remarkably good repeatability.

In conclusion, sensitive layers in a quarter-wave polarizer design are optimized to non-quarter-wave ones; the polarizer zone is broadened in such cases when the total layer thickness does not increase. In this setup, an automatic thickness control system is established, with which the cutting point can be automatically calculated. Thus, the influences caused by subjective factors can be eliminated, including such zones with  $T_p$  higher than 98% and  $T_p/T_s$  higher than 200:1, and with the bandwidth of 11 nm. The polarizer prepared with this system shows high performance and optimum repeatability.

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