Determining polymer film thickness during manufacturing with broadband transmission

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A novel broadband transmission method to determine polymer film thickness during manufacturing is proposed, and a measurement system is developed based on this method. The relationship between broadband optical power and film thickness is deduced according to the Lambert–Beer law. The system is composed of a halogen light and an optical power meter. Results show that the measurement error of this method is approximately 1 μm, and the resolution of the system is below 0.4 μm for polymer films with less than 100-μm thickness.

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Polymer films are two-dimensional chemical materials that have important roles in agriculture, packaging[1], separation membranes[2], sensor films[3], and numerous other fields. Film thickness is a key parameter related to quality that affects a variety of other properties, such as tensile strength and transparency[4,5]. Therefore, a method should be developed to measure film thickness accurately and rapidly during manufacturing. Unfortunately, many film thickness measurement techniques, including microscopy[6], spectroscopy[7], interferometry[8,9], ellipsometry[10], and optical dyes[11], are not designed for process monitoring because these methods are time consuming and not robust to environmental disturbance. Other methods can be used to determine film thickness in production processes. The ray technique[12] has been successfully used in the film production line, but the danger of radioactive materials restricts its further development. Optical techniques can also be used to determinate film thickness by measuring the distance between the film upper surface and roller[13,14]. However, the flutter of the roller usually produces measurement errors. Acoustic microscopy and infrared diffuse reflectance spectroscopy have been investigated for real-time analysis of tablet coating thickness in the pharmaceutical industry, but their applications in other industries are still under research[15].

Thus far, transmission methods[16,17] whose rationale is the Lambert–Beer law are promising for film thickness monitoring in production processes. The basic technique is monochromatic transmission, but dual-wavelength light contrast method is often used to counterbalance disturbance and drift[18−20]. The two monochromatic lights do not strike the same position on the film because the lights strike successively and the film moves fast in the production line, thereby decreasing accuracy. When the broadband transmission method[21] is used to determine film thickness, the attenuation of the broadband light intensity is analyzed to achieve higher accuracy. Furthermore, the attenuation bands of different kinds of films evidently differ. Thus, the selection of wavelengths may not be altered when using this method to measure the thicknesses of different kinds of films. That is, this method exhibits better universality.

In this letter, the relationship between broadband optical power and film thickness is deduced first because the Lambert–Beer law is relevant to monochromatic light only. Then, a measurement system is developed on the basis of the broadband transmission method. The measurement resolution and error of this method are analyzed.

According to the Lambert–Beer law, monochromatic light at a wavelength of λ and whose spectral intensity is $I_{0\lambda}$ attenuates when it passes through a material because of absorption and scattering.

The spectral intensity of the transmission light I_λ can be expressed as

$$I_\lambda = I_{0\lambda} \exp(-\alpha_\lambda t), \tag{1}$$

where α_λ is the extinction coefficient of the material and t is the optical distance.

When light passes through a polymer film, attenuation may be analyzed from two aspects. On one hand, light reflex occurs on the two surfaces of the film, which is not significantly influenced by film thickness. On the other hand, the absorption and scattering of the film weaken light intensity, which follows the Lambert–Beer law. Therefore, by using τ_λ to represent the spectral transmission and a_λ to represent the attenuation rate independent of thickness, we can obtain the film intensity attenuation model shown as

$$\tau_\lambda = \exp(-\alpha_\lambda t) - a_\lambda. \tag{2}$$

Then, Eq. (1) can be rewritten as

$$I_\lambda = I_{0\lambda} \exp(-\alpha_\lambda t) - I_{0\lambda} a_\lambda. \tag{3}$$

By integrating Eq. (3) in spectral bands λ_1 to λ_2, we obtain

$$\int_{\lambda_1}^{\lambda_2} I_\lambda \mathrm{d}\lambda = \int_{\lambda_1}^{\lambda_2} I_{0\lambda}[\exp(-\alpha_\lambda t) - a_\lambda]\mathrm{d}\lambda. \tag{4}$$

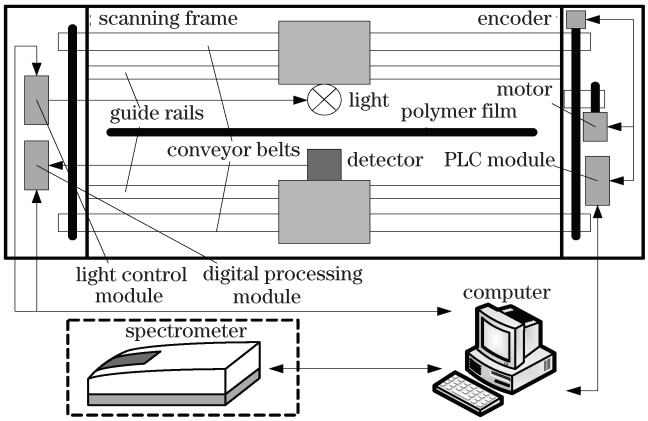

Fig. 1. Schematic of the measurement system.

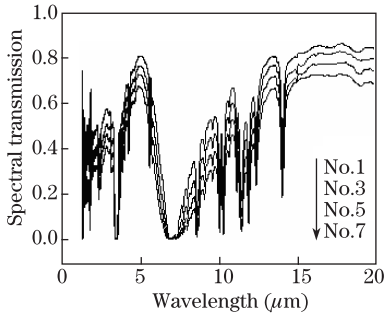

Fig. 2. (Color online) Spectral transmissions of films.

For the proposed measurement system, $I = \int_{\lambda_1}^{\lambda_2} I_\lambda \mathrm{d}\lambda$ is the intensity of the illuminant in the spectral band from λ_1 to λ_2. According to the definition of intensity, we obtain

$$P = KI, \tag{5}$$

where P is the optical power received by the thermopile detector and K is the coefficient converting intensity to optical power, which is a constant when the relative position of the light and detector is unchanged. Using Eqs. (4) and (5), we obtain

$$P = K \int_{\lambda_1}^{\lambda_2} I_{0\lambda}[\exp(-\alpha_\lambda t) - a_\lambda]\mathrm{d}\lambda, \tag{6}$$

where $I_{0\lambda}$ can be measured with a spectrometer, and α_λ and a_λ can be obtained by fitting Eq. (2) with a set of film transmissions with different thicknesses. When the optical power received by the detector has been obtained, film thickness can be calculated by inverting Eq. (6).

The measurement system shown in Fig. 1 is composed of a spectrometer, a halogen light, an optical power meter, a computer, and an O-shaped scanning frame. A spectrometer (6100, JASCO, Japan) is used to measure the spectral transmissions of films and spectral relative energy of the illuminant. Given that the measurement system operates in the production line, a spectrometer is no longer needed. The optical power meter (RkT-10, Laser Probe, USA) has a spectral response ranging from 0.2 to 20 μm. The halogen light and optical power meter, which are installed on conveyor belts, are moved along the guide rails by a motor when the system operates. The intensity of the illuminant is regulated by the light control module, and the movement of the conveyor belts is controlled by the programmable logic controller (PLC) module. The digital processing module transforms optical power to digital signal and then sends it to the computer at 5 Hz. The computer receives the measurement position information obtained by the encoder through the PLC module. Thus, the computer determines the film thicknesses at different positions.

In our experiment, polypropylene films are selected as the test subject. The films are obtained from the Jingwei branch of Foshan Plastic Group Inc. By adjusting the extruder bolts in the production line, we obtain some films with different thicknesses. Seven films are selected and numbered from 1 to 7, with thicknesses of 71.4, 79.7, 90.6, 99.8, 110.2, 120.6, and 131.5 μm.

We set the spectrometer at 4 cm^{-1} resolution, and five scans are conducted for every test. The transmissions of the films are measured, and Nos. 1, 3, 5, and 7 films are shown in Fig. 2. The intensity of attenuation is significantly related to film thickness in almost the whole spectral range.

To improve system resolution, the illuminant intensity must be as high as possible. Thus, we adjust the illuminant power supply so that the optical power received by the detector reaches 100 mW, which is the maximum of the optical power meter range when no film is placed between the light and the detector. The spectral relative energy of the illuminant is measured using a spectrometer, as shown in Fig. 3.

We use Eq. (2) to fit the extinction coefficient (α_λ) and attenuation rate independent of thickness (a_λ) with the set of film transmissions and thicknesses. The fitting results are displayed in Fig. 4. Zero values of a_λ are observed in spectral bands from 5 to 6 μm and

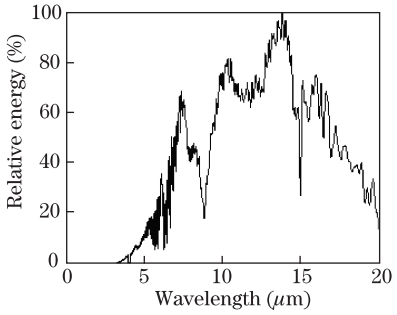

Fig. 3. Spectral relative energy of the illuminant.

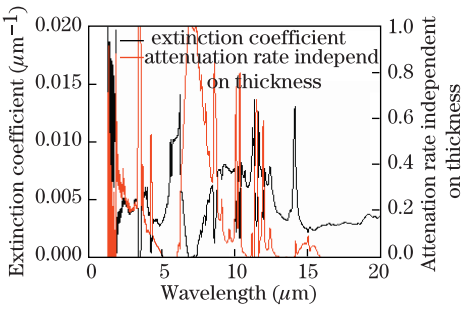

Fig. 4. (Color online) Spectral distribution of extinction coefficient and attenuation rate independent of thickness.

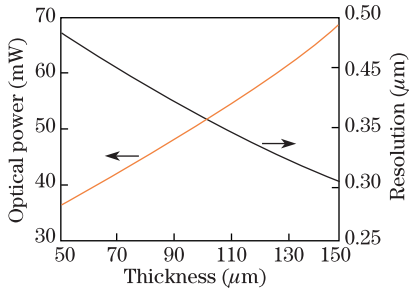

Fig. 5. Relationship between optical power and film thickness and resolution of the measurement system.

Table 1. Calculated Values of Film Thickness and Their Errors (μm)

Number	1	2	3	4	5	6	7
Thickness	71.2	79.6	90.1	101.1	110.8	119.6	131.3
Error	–0.2	–0.1	–0.5	1.3	0.6	–1	–0.2

from 16 to 20 μm, which indicates that the intensity attenuation in these bands is due to the absorption and scattering of the film. The curve of a_λ approximates 1 in the spectral bands around 3 and 7 μm, indicating that intensity attenuation is not due to thickness. The curve of α_λ approximates 0 in these bands, thereby confirming this finding. This analysis proves the rationality of the film intensity attenuation model (Eq. (2)) to some extent.

Afterward, we determine the value of coefficient K in Eq. (6). When no film is placed between the light and detector, the optical power received by the detector can be deduced by

$$P = K \int_{\lambda_1}^{\lambda_2} I_{0\lambda} \mathrm{d}\lambda. \tag{7}$$

The value of $\int_{\lambda_1}^{\lambda_2} I_{0\lambda} \mathrm{d}\lambda$, which can be calculated from Fig. 3, is 7.93 mW/sr. Substituting P=100 mW into Eq. (7), we obtain K=12.61 sr.

Thus, the values of the undetermined coefficients in Eq. (6) are obtained. Then, Eq. (6) is used to calculate the optical power received by the detector when the film thickness ranges from 50 to 150 μm. The relationship between optical power and film thickness is shown in Fig. 5. An approximately linear relationship is observed because the range of film thickness is relatively small. The slope (absolute value) of the curve and the system resolution decrease as the film thickness increases. The system resolution determined from the resolution of the optical power meter is 0.1 mW (Fig. 5). The system resolution is below 0.4 μm for conventional films, which have less than 100 μm thickness.

We use seven films with unknown thicknesses to estimate the accuracy of this thickness measurement method. The optical power can be deduced by the following align if light passes separately through the seven films.

$$P = K \int_{\lambda_1}^{\lambda_2} I_{0\lambda} \tau_\lambda \mathrm{d}\lambda. \tag{8}$$

Film thickness is calculated by inverting Eq. (6). The calculated values of film thickness and their errors are shown in Table 1.

In conclusion, a broadband transmission method is proposed for determining polymer film thickness during manufacturing, and a measurement system is developed based on this method. The spectral distribution of film extinction coefficient and attenuation rate independent of thickness can be obtained by using the film intensity attenuation model, which may be useful in the chemical industry for the analysis of the spectral characteristics of polymer films. The measurement error of this method is approximately 1 μm and the resolution of the system is around 0.4 μm, which generally meet the needs of polymer film production.

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