High-Precision Online Infrared Sensor WG51S2

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In recent years, there has been growing demand for films as functional materials that are utilized across a wide range of fields from packaging to electronic devices. The trend toward thinner films reflect the need for portioned food packaging and lightweight, slim electronics. By measuring the thickness of films online during the manufacturing process, advanced quality control of film thickness becomes possible. The infrared sensor WG51S2, part of the online thickness gauge WEBFREX NV, allows for high-precision thickness measurement during the film manufacturing process. With the adoption of detectors tailored to the trend toward thinner films, this enhancement enables highly sensitive thin film measurements, strengthens the functionality and stability of the infrared sensor, and improves quality control capabilities.

INTRODUCTION

Plastic films are widely used in various applications, from food packaging to electronic components, improving performance such as shelf life for foodstuffs and the optical characteristics of LCD panels[(1)(2)]. With the growing demand for small-portion food packaging and slim, lightweight electronic devices, films are becoming increasingly thinner. There is also a growing demand for high-performance films for use in applications such as separators for secondary batteries as a result of the increasing demand for electric vehicles. Against this backdrop, advanced quality control in film manufacturing has become essential.

In 2015, Yokogawa Electric Corporation developed its online thickness gauge WEBFREX NV, and in 2018, we commercialized the infrared sensor WG51S2[(3)] for installation in this system. This infrared sensor accurately measures quality characteristics related to film thickness. This sensor moves across the width of the film during the production process, sending the measured thickness values at each point to the system. In this way, a thickness profile is obtained, which is used to evaluate the thickness uniformity of the film. The thickness profile data can be fed back to the thickness control system to enhance the uniformity of the product.

This infrared sensor achieves measurement accuracy on the same level as that of a radiation-type thickness sensor and achieves high robustness by using Yokogawa's proprietary optical system. In this paper, we report on an infrared sensor that improves the stability of thin-film thickness measurement by using an infrared detector with a wide measurement wavelength range.

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BASIC OPERATION OF THE INFRARED SENSOR WG51S2

Measurement Principle

Each material has a unique absorption wavelength. Infrared sensors generally calculate thickness by exploiting the property in which the amount of infrared light absorbed when passing through an object varies according to its thickness. Measurements of the thickness of films, which are polymeric structures, utilize the absorption of infrared light associated with molecular vibrations and rotations of CH groups and other molecular structures.

Figure 1 shows the infrared absorption spectrum of a polypropylene film. The infrared sensor WG51S2 corrects the absorbance of wavelength M according to the light intensities of reference wavelengths R1 and R2 in order to compensate for the turbidity of the material and variations in the position of the film relative to the sensor (pass-line fluctuation), thereby enabling accurate and stable film thickness measurements.

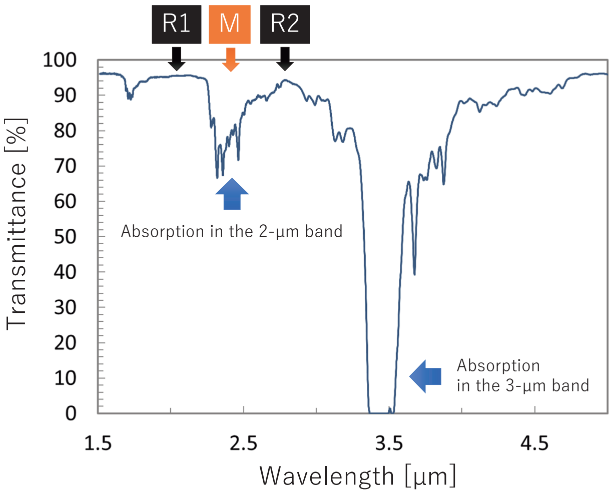

Figure 1 Infrared absorption spectrum of polypropylene film

Features of the Infrared Sensor WG51S2

The infrared sensor WG51S2 combines Yokogawa's proprietary optical system, which uses a frequency-modulated light source and dual integrating spheres with a digital lock-in amplifier circuit to detect micro-signals, dramatically improves accuracy and reliability. Figure 2 shows the WG51S2's appearance, and Table 1 lists its main specifications.

Figure 2 Appearance of the infrared thickness sensor WG51S2

Table 1 Main specifications of the infrared thickness sensor WG51S2

Item	Specification
Light source	Halogen lamp
Photodetector	• InGaAs detector • PbSe detector Note: Selected according to the measurement thickness range
Wavelength discrimination method	Frequency modulation Lock-in amplifier
Thickness measurement range	5 to 2000 μm
Mean value repeatability	±0.2 μm or ±0.2% (whichever is greater) Maximum accuracy: ±0.1 μm*1
Measurement optics	Diffusion optics
Thin-film interference control method	Angle averaging method
Elimination of disturbances and heat	Lock-in detection
Allowable pass line	±10 mm

*1For a 20-μm-thick polypropylene film

Dual Integrating Spheres

Figure 3 shows a schematic of the dual integrating spheres, which are provided on both the light-source side and the detection side. Light emitted from the integrating sphere on the light-source side passes through the film and enters the integrating sphere on the detection side. As the detection-side integrating sphere receives light, light at angles not received pass back through the film from the detection side toward the light-source side. Light passing through the film is captured at the light-source side, reflects off the integrating sphere's inner wall, and passes through the film again. Having the light pass through the film multiple times in this manner produces a high signal-to-noise ratio. Additionally, the wide-angle, non-directional diffused light can invalidate the conditions for the occurrence of thin-film interference. Furthermore, diffused light substantially reduces measurement errors in online measurements involving sensor movement. Yokogawa has patented this unique dual integrating-sphere optical system in Japan (Patent No. 6394825).

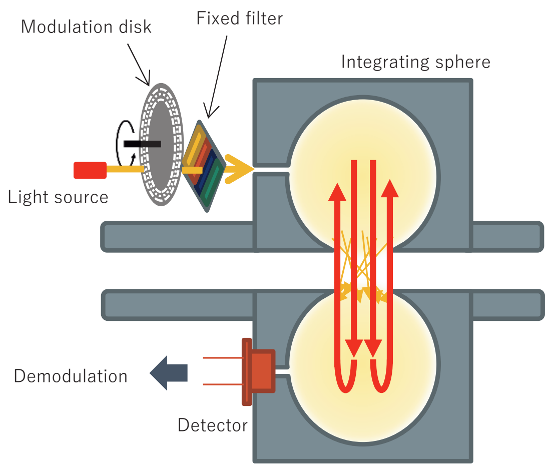

Figure 3 Dual integrating spheres structure

This optical system with dual integrating spheres cancels out the influence of the film's transmission position, making it resistant to pass-line variations. Although the generally allowable pass-line variation is within several millimeters, this system allows for variations of ±10 mm, making it less susceptible to the effects of flow fluctuations (oscillations), wrinkles, and curling at the edges of films. The allowable pass-line variation is superior to that of competing products and is a notable feature of the infrared sensor WG51S2.

Digital Lock-in Detection

Our lock-in detection technology is a micro-signal detection technique that achieves a high signal-to-noise ratio by extracting signals in the desired frequency band and efficiently removing all other frequency components. Figure 4 shows the structure of the frequency-modulated light source.

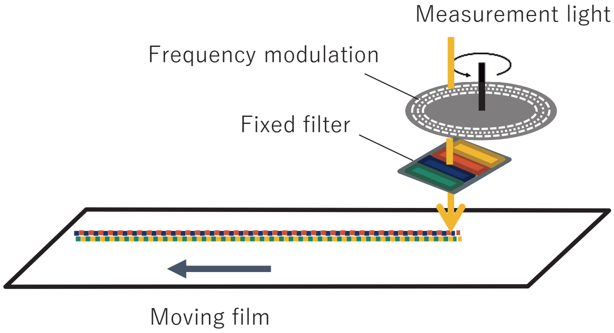

Figure 4 Frequency modulation light source structure

The measuring light irradiated onto the sample is modulated at three frequencies, and three optical filters extract the desired wavelengths, which are mixed in an integrating sphere and irradiated onto the measured film. The light that the detector receives is converted into an electrical signal. Then, the digital lock-in detection circuit extracts only the respective frequencies, and the extracted measurement signals are converted into DC signals corresponding to the intensity of each frequency. The low-pass filter, which passes only the output DC signals, narrows the extracted frequency band by filtering compared with a bandpass filter. This eliminates thermal radiation from the film itself, which is fabricated at high temperatures, as well as stray light from the installation environment, 1/f noise in the range of several to tens of hertz, and thermal noise, thereby enabling thickness measurements with a high signal-to-noise ratio.

Furthermore, because this method enables simultaneous same-point measurements on the film, those measurements are less susceptible to the influence of baseline fluctuations. Note that the widely used method of switching optical filters allows the measuring light to measure only one wavelength at a time. Therefore, the timing of measurement by the measuring light and the reference light differ, and it is impossible to eliminate the effects of signal intensity changes due to pass-line variations, stray light, and baseline fluctuations caused by film clouding, making stable measurements difficult. In contrast, using the digital lock-in method, a single detector simultaneously performs intensity measurements of the measuring light and two reference lights, each chopped and modulated at different frequencies, and digital lock-in detection discriminates the measurement signals for each frequency. This allows for simultaneous measurement of not only the measuring light for measuring transmission absorption but also the reference lights for baseline corrections, thereby enabling measurements that reliably eliminate the effects of external disturbances. The ability to simultaneously measure three measuring lights with a single detector using this frequency chopping and lock-in technology is another advantage of the method. When preparing detectors for each measurement wavelength, sensitivity variations among the detectors can lead to measurement errors. However, when there is only one detector, even if the detector sensitivity fluctuates, signal magnitudes change for the signals at all wavelengths, enabling the use of reference lights to correct absorbance. In addition to eliminating detector sensitivity errors, this simultaneously reduces calibration efforts, lowers failure risk, and reduces costs.

PROBLEM AND TECHNICAL SOLUTION

Problem

The infrared sensor WG51S2 was already capable of stable measurements that are robust against environmental changes, but its measurements for thin films were less stable compared with thick films. This was due to limitations in the range of the installed detector's measurement wavelengths, which were restricted to 3 µm or less. In particular, the range above 3 µm contains wavelengths with high absorption rates corresponding to the stretching vibrations of CH groups in the films. For example, the absorption spectrum of the polypropylene film in Figure 1 shows that the absorption at a wavelength of 3.4 µm is more than double that at 2.3 µm. Performing transmittance measurements in this region above 3 µm would result in a large signal change due to absorption, even with thin films, thereby enabling measurements with a high signal-to-noise ratio.

Measurement Wavelength Range

Film materials absorb infrared light at specific wavelengths. It is thus important to select an appropriate wavelength when measuring film thicknesses.

The range from 750 to 2500 nm is called the near-infrared region, and many film materials have unique absorption bands in this range. The transmittance change in this band is relatively small, making it suitable for stably measuring relatively thick films of 100 µm or more.

The range from 2500 to 8000 nm is called the mid-infrared region, and organic materials and many polymers exhibit strong infrared absorption in this region. This mid-infrared wavelength band often features absorptions where the transmittance changes significantly, enabling the thickness of thin films to be measured with high sensitivity because small changes in thickness result in large changes in transmittance.

Detector Selection

Our previous infrared sensor used an indium gallium arsenide (InGaAs) photodiode as its detector. That detector had high measurement sensitivity and a fast response speed, making it well-suited for application as an infrared sensor. However, with a maximum wavelength of 2.5 µm, its spectral sensitivity characteristics were limited to the near-infrared region. To achieve high-sensitivity measurements of thin films, it was necessary to extend the detection wavelength range.

There are various types of detectors for measuring mid-infrared light, including indium arsenide (InAs) or indium antimonide (InSb) photovoltaic detectors, lead selenide (PbSe) or lead sulfide (PbS) photoconductors, and thermopile detectors, each having its own characteristics. To improve measurement performance, it is important to select a detector suited to the intended application, especially considering factors such as spectral sensitivity characteristics, response speed, size, and ambient temperature.

For this application, we adopted a PbSe detector capable of high-sensitivity measurements over a wide infrared wavelength range. The PbSe detector has sensitivity in the near- to mid-infrared region from 1.0 to 5.5 µm. Expanding the upper limit of the measurement wavelength range from 2.5 to 5.5 µm made it possible to measure with high sensitivity thin-films made of materials that exhibit strong absorption in this region. It also became possible to measure new film materials with absorption in this region, broadening the material types that can be measured. Furthermore, the response speed is fast, around several microseconds, which is well-suited for the frequency discrimination and lock-in detection technologies that are characteristics of this thickness sensor. The detector element is also a large 6 mm × 6 mm, making it possible to efficiently receive light diffused from the dual integrating spheres. For these reasons, the PbSe detector is suitable for the measurement technology of this thickness sensor and exhibits enhanced functionality compared with the conventional thickness sensor.

PbSe Detector

The PbSe detector is a photoelectric device for fast, high-sensitivity measurements of infrared light intensity. When this detector is exposed to infrared radiation, the electrical conductivity changes according to the incident light intensity. This enables the acquisition of a measurement light intensity signal by applying a bias voltage across the detection element in the detection circuit.

Detector Temperature Control

When using a detector to measure infrared light, it is necessary to keep its temperature low to improve its sensitivity and performance. The detector dark current increases as its temperature rises, becoming a noise source when accurately detecting the target signal. The detector has a low dark current at low temperature, which improves the signal-to-noise ratio.

In addition, thermal energy increases as the temperature rises, so thermal noise is generated in the detector in a high-temperature environment. Because thermal noise causes noise in the detection signal, lowering the element temperature suppresses noise and improves the measurement accuracy.

For these reasons, it is important to maintain a low detector temperature to improve the infrared detector's performance and ensure its reliability. The detector in the developed infrared sensor uses Peltier cooling to maintain the detector temperature at a constant 0°C with an accuracy of 0.1°C or less.

Stabilization of the Measurement Thickness Range

Figure 5 shows example measurement results for a polyethylene film with a width of 2000 mm and a thickness of approximately 25 µm. This profile was measured by the infrared sensor installed on a WEBFREX NV system and the raw data were overlaid ten times without averaging. The vertical axis is plotted with a scale of 0.2 µm per division.

The profile was more stable and less variable compared with the measurement results obtained using a sensor equipped with an InGaAs detector.

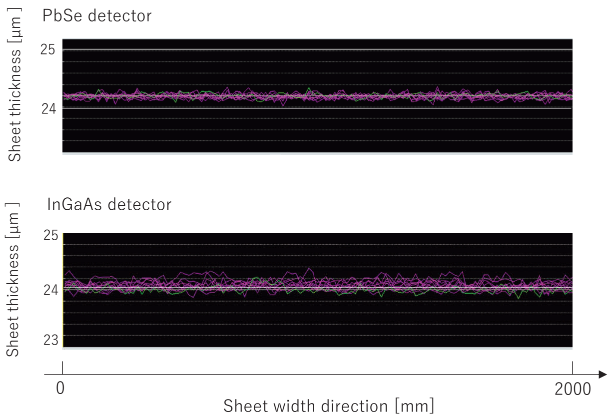

Figure 5 Measurement results for a polyethylene sheet (sample testing)

CONCLUSION

In response to the trend toward thinner film, a new detector capable of stably and accurately measuring thin films was integrated into Infrared Sensor WG51S2. This integration resulted in an expanded range of thickness measurements. Additionally, the types of materials that can be measured have also increased. Consequently, while leveraging conventional features such as simultaneous measurement and high stability, constraints were overcome, enabling use of the sensor in a wide range of applications.

In the future, we plan to install the developed sensor in the QC1F16 frame for the WEBFREX NV, which complies with international standards. Furthermore, the digitalization technologies introduced with this frame are expected to enable real-time monitoring of the infrared sensor's condition, dramatically improving its maintainability.

We are also considering further expanding the range of applications by increasing the number of simultaneously measurable wavelengths.

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